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NONLINEAR OPTICAL (NLO) POLYMER OPTO-ELECTRONIC DEVICES

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This document reviews work that supported the Cooperative Research Agreement CRDA 96-101-WL-01 between AdTech Systems Research, Inc. and the Air Force Research Laboratory (AFRL). Prior to the formation of AFRL, the agreement was with Wright Laboratory. The objective of the CRDA was to utilize AdTech's Nonlinear Optical (NLO) polymers in an electro-optical waveguide switch. The report reviews electro-optic (E-O) modulators, especially the zero-gap directional coupler. A nonlinear material with a reliable coefficient of 10 pm/V was needed. That was never achieved, therefore, after four years the CRDA was cancelled.

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This manuscript covers in-house work spanning a number of years and was funded by the Air Force Research Laboratory (AFRL).

SUMMARY

This document reviews work that supported the Cooperative Research Agreement (CRDA) between AdTech Systems Research and the Air Force Research Laboratory (AFRL). The objective of the CRDA was to utilize AdTech's Nonlinear Optical (NLO) polymers in an electro-optical waveguide switch.

The document reviews the science behind the Mach-Zehnder electro-optic modulator, the directional optical coupler and practical NLO polymer electro-optical waveguide devices. Mathematical models of rectangular dielectric waveguides are explored. The computer aided design program Beam PROP is explored. Device fabrication techniques are reviewed. Consideration is given to the zero-gap directional coupler and the use of a conductor for the cladding layer.

A requirement for AdTech Systems Research was that their material would be reproducible and have an electro-optical coefficient of at least 10 pm/V. The NLO polymer did not meet that requirement, therefore, AFRL did not fabricate any waveguides. Due to a change in the direction of the Aerospace Components Division of the Sensors Directorate of AFRL and the lack of a reproducible NLO material meeting the coefficient requirement, the CRDA was cancelled.

1.0 INTRODUCTION

Air Force electronics systems require high speed operation that is beyond the capabilities of present day device packaging. The individual devices run so fast that the time it takes for the signal to get from one package to another limits system speed. One approach toward solving that problem is to package devices in multichip modules (MCMs) that place many devices very close together. Inter-chip and inter-package signal transfer is still to slow. The technology that is being developed commercially is based on fiber optic cables. Modulation of the light utilized by fiber optics requires an independent, electrically modulated laser. The electronic drivers are current not voltage drivers. Each laser requires a significant amount of power. Such an electronic driver running at multi-gigahertz rates takes up considerable area. An array of electrically driven lasers in a MCM is not practical. An alternative is to electrically modulate optical waveguides. Waveguides, as insulators, are voltage driven not current driven. Voltage driven waveguide modulators can have considerably less power requirements than lasers. Waveguides can, conceivably, be TTL driven. Therefore, active waveguides may be compatible with MCMs for data transfer.

This report covers the Cooperative Research and Development Agreement (CRDA) between AdTech Systems Research Inc. located at 1342 N. Fairfield Road, Beavercreek, Ohio 45432 and the United States of America a represented by the Department of the Air Force, Air Force Materiel Command, Aeronautical Systems Center, Air Force Research Laboratory (AFRL), Sensors Directorate, located at Wright-Patterson Air Force Base, Ohio. The designated USAF CRDA number for the effort was 96-101-WL-01. Ad Tech developed new materials and has demonstrated large scale synthesis of samples of various organic NLO materials. AFRL's Sensors Directorate had an active program to develop NLO devices and had the expertise in the fabrication and testing of representative devices and test structures. Such testing is essential to for the understanding of the materials-device interactions. AFRL's Materials Directorate (AFRL/ML) has the facilities and capabilities for using polymeric NLO materials to

produce thin films on indium tin oxide (ITO) glass, silicon wafers. AFRL/ML has the capability of polling NLO films.

The purpose of the CRDA was to fabricate and characterize devices using new organic nonlinear optical (NLO) materials. The NLO devices to be fabricated were optical waveguide switches. The devices could be used in any application that could benefit from the high-speed manipulation of light beams. The transmission of signals from one chip to another will one day be optical.

The technical effort by AFRL was not to be initiated under the CRDA until a three-layer film having the following characteristics was available:

a. A minimum electro-optic (EO) coefficient of 10 picometers per volt measured at 150 °C.
b. A propagation loss not to exceed 2 decibels per centimeter (dB/cm) measured at a nominal wavelength of 800 nm ± 50 nm.

While, the technical activity that AFRL was to perform was as follows:

a. Conduct nonlinear optical measurements using the NLO triple-stack film materials provided by Ad-Tech.
b. Using the NLO triple-stack material, design and fabricate the following waveguide devices:
   i. Two passive directional coupler switches
   ii. Two active directional coupler switches
   iii. Two Mach Zehnder switches
c. Determine the switching voltage and interaction length of the active waveguide devices

While not part of this CRDA, Dr. James G. Grote submitted two patent applications on conductively clad electro-optical waveguides. The patents were granted in 1999. The patents are US patent numbers 5,887,116 and 5,892,859 and are in the Appendix. If the core NLO material of AdTech had an adequate coefficient, it was the intent to apply the ideas of the patents for the AdTech material.

For our analysis we will consider an optical field that is incident and normal to the xz plane propagating along the y axis with E parallel to the z axis. At the input plane y = 0, the optical field can be resolved into two mutually orthogonal components polarized along x and z. The x component propagates as [1, 2]

$$E_x = A\exp[i(\omega t - (\omega/c)n_x z)], \tag{1}$$

where ω is the angular frequency, t is time and A is a constant. The z component propagates as [1, 2]

$$E_z = A\exp[i(\omega t - (\omega/c)n_z y)]. \tag{2}$$

The difference in phase between these two components at the output plane y = L is called the phase retardation [1, 2]. It is given by the difference of the exponential terms in Equations (1) and (2). Performing the subtraction yields

$$\Gamma_{xz} = (\omega/c)(n_z - n_x)L, \tag{3}$$

where $[n_z - n_x]$ is the induced birefringence found in the previous section. Substituting for the induced birefringence gives [1, 2]

$$\Gamma_{xz} = (\omega/c)((n_e - n_o) - ((n_e^3/2)r_{33} - (n_o^3/2)r_{13})E)L. \tag{4}$$

Using the relation $\omega/c = 2\pi/\lambda$ with λ defined as the wavelength, the phase retardation becomes [2, 3]

$$\Gamma_{xz} = (2\pi/\lambda)(n_e - n_o)L - (\pi/\lambda)(n_e^3 r_{33} - n_o^3 r_{13})VL/d, \tag{5}$$

where V is the voltage applied between electrodes separated by a distance d. Due to the natural birefringence term in Equation (5), a Babinet or Soleil phase compensator will be required. This will allow us to adjust the phase retardation, that is present in the absence of the applied voltage, to equal an odd integral multiple of $\pi/2$. We then want a voltage dependant phase retardation of 180°, or $\Gamma_{xz} = \pi$. The voltage necessary to realize a π phase change is defined as half wave voltage [1, 2]. Equating the voltage dependant phase term of Equation (5) to π gives us [4]

$$V_{\pi} = d\lambda/L(n_e^3 r_{33} - n_o^3 r_{13}). \tag{6}$$

V_{π} is the voltage necessary to realize half wave polarization in tetragonal crystals.

Figure 1 illustrates a Mach Zehnder (MZ) interferometer.

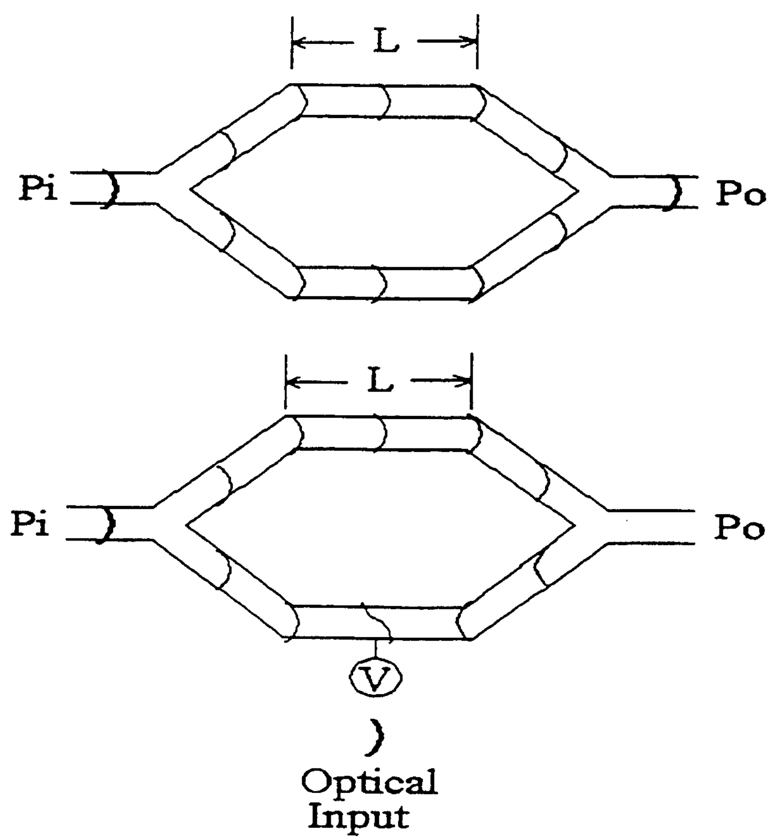

Figure 1. Mach Zehnder Interferometer.

interferometer is a form of transverse electro-optic modulator. The input signal is first split equally into two separate channels. These two channels are separated by enough distance to prevent any crosstalk or coupling. The two channels are later recombined back into one channel. Voltage is applied to only one of the separated channels. When voltage is absent, half of the signal propagating in channel one recombines constructively with half of the signal propagating in channel two, and the output equals that present at the input. Voltage applied to one of the channels results in a phase shift of the propagating beam only in that channel. When enough voltage is applied to shift the phase of the beam in that channel by π, then half of the signal propagating in channel one recombines destructively with half of the signal propagating in channel two, and the output becomes zero. By periodically switching the voltage on and off, one can realize sinusoidal modulation of the optical signal.

3. DIRECTIONAL COUPLERS

The directional coupler switch is a device consisting of parallel channel waveguides separated by a finite distance. The coupling between the modes of the parallel waveguides results in an exchange of power between guided modes of adjacent waveguides [4]. This is referred to as directional coupling. The eigenmodes of the coupling region consist of one symmetric and one antisymmetric mode [1, 4-11]. Treatment of waveguide coupling can be performed by coupled-mode theory [1, 5, 7, 8].

A directional coupler is illustrated in Figure 2. In the figure, s is the separation between the waveguides.

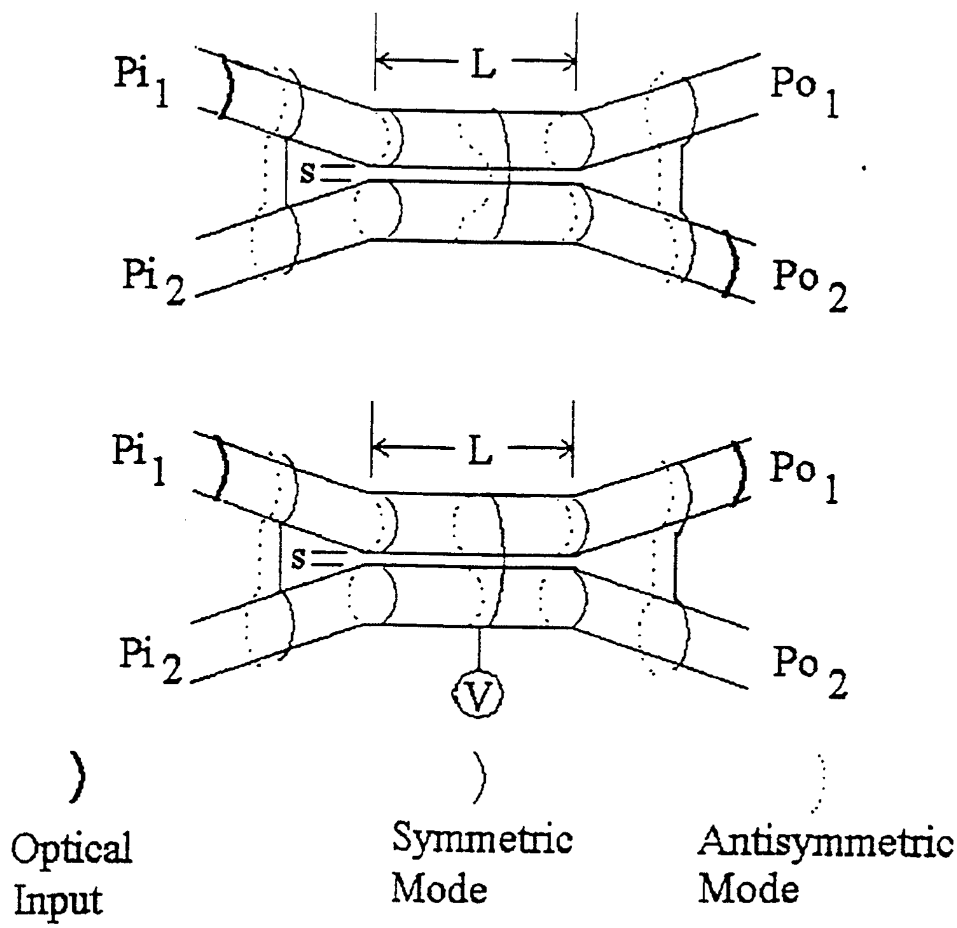

Figure 2. Operation of a Directional Coupler

Consider Pi_1 as the input power to waveguide 1, Pi_2 as the input power to waveguide 2, Po_1 as the output power from waveguide 1 and Po_2 as the output power from waveguide 2. Let waveguide 1 propagate through the symmetric mode and waveguide 2 propagate through the antisymmetric mode. Assume that the waveguides are not too close, so that the overlap integral of the mode functions will be small [1, 4, 7, 8]. With a single input to waveguide 1, $Pi_1 = 1$ and $Pi_2 = 0$, the output power from waveguides 1 and 2 are given as [1, 4, 7-9]

$$Po_1(l) = Pi_1 - Po_2(l) = Pi_1(1 - (\kappa^2/(\kappa^2 + \delta^2))(1 - \cos^2[(\kappa^2 + \delta^2)^{1/2}(l)])) \tag{7}$$

and

$$Po_2(l) = Pi_1((\kappa^2/(\kappa^2 + \delta^2))(\sin^2[(\kappa^2 + \delta^2)^{1/2}(l)])), \tag{8}$$

where $2\delta = \beta_1 - \beta_2$ is the difference in the propagation constants between two adjacent uncoupled waveguides 1 and 2, κ is the coupling constant between the two adjacent waveguides. l is the interaction length over which the two waveguides are coupled. By definition, $\kappa = \pi/2L$, where $l = L$ is the length required for complete coupling of the power from one waveguide to the other [1, 4-16].

For symmetric waveguides, the phase velocities in the two modes are equal (i.e., $\beta_1 = \beta_2$ or $\delta = 0$). For complete coupling, [1, 4, 7-9]

$$Po_1(L) = Pi_1(1 - (1 - \cos^2[\pi/2])) = 0 \tag{9}$$

and

$$Po_2(L) = Pi_1(\sin^2[\pi/2]) = Pi_1. \tag{10}$$

From Eqs. (7) and (8), one can see that the input power Pi_1 into waveguide 1 will exit waveguide 2 as Po_2 at a distance L. Using Eqs. (9) and (10), complete coupling occurs when $L = \pi/2\kappa$.

Applying an electric field to either waveguide 1 or waveguide 2 over the distance L, where the waveguides are coupled, will change that particular waveguide's propagation constant β. Total switching occurs when $\delta = 3^{1/2}\pi/2L$ [4 , 8, 9]. This can be verified by the substitution of $\delta = 3^{1/2}\pi/2L$ into Eqs. (7) and (8). By doing this, we get [1, 4, 7-9]

$$Po_1(L) = Pi_1(1 - (1/4)(1 - \cos^2[\pi])) = Pi_1 \tag{11}$$

and

$$Po_2(L) = Pi_1((1/4)(\sin^2\pi])) = 0. \tag{12}$$

Using the definitions for δ and κ given above, one gets total switching to occur when [1, 4, 7, 8]

$$(\beta_1 - \beta_2) = 3^{1/2}\pi/L. \tag{13}$$

If we apply an electric field (E) over waveguide 2, for instance, this will induce a change in the refractive index of waveguide 2 by an amount proportional to E. Mathematically, this is given by [1, 2, 4, 7, 8]

$$\Delta n_2 = (n_2^3/2)rE, \tag{14}$$

where n_2 is the refractive index of waveguide 2 and r is the electro-optic coefficient of the waveguiding material. To apply an electric field to one of the waveguides, we place electrodes on the top and bottom of the waveguide over the coupling length (L) and apply a voltage (V) to the top electrode. The electric field is then related to the applied voltage by V = Ed, where d is the distance between the top and bottom electrode. The total index (n_2') of the waveguide 2 region between the electrodes can be defined by

$$n_2' = n_2 + \Delta n_2 = n_2 + (n_2^3/2)rV/d. \tag{15}$$

By definition, $\beta = 2\pi n/\lambda$, where λ is the wavelength of the source [1, 4, 7, 8]. If we let waveguide 1 and waveguide 2 be identical ($n_1 = n_2 = n$), and substitute Eq. (15) into (13),

along with the definition for β, this yields [1, 4, 7, 8]

$$(2\pi/\lambda)(n' - n)(n^3/2)(rV/d) = (2\pi/\lambda)(n^3/2)(rV/d) = 3^{1/2}\pi/L. \tag{16}$$

We can now find the voltage required to switch the coupling completely. By rewriting Eq. (16), we get

$$V = (3^{1/2}\lambda d)/(n_2^3 rL). \tag{17}$$

The EO coefficient $r = r_{33}$ can be substituted for the assumed crystal orientation presented in the previous section.

3.1 Zero-Gap Directional Couplers

As with directional couplers, the interaction region of a zero-gap directional coupler will support two guided symmetric modes, and two guided antisymmetric modes [17-24]. The difference between them, however, results from the fact that we have zero spacing between the two symmetric waveguides in a zero-gap directional coupler. These modes will now be propagating in a single waveguide. We will again have a voltage independent phase difference that accumulates over the interaction length (the two mode section), due to the difference in the phase velocities of the two orthogonal modes, and a phase difference over the two mode section, brought about by the voltage induced change in refractive index (EO effect) [4, 25-28].

The electro-optic dependent phase difference will be denoted by $(\beta_s - \beta_{as})/2 = \Delta\beta/2$, where β_s and β_{as} are the propagation constants of the symmetric and antisymmetric modes, respectively [18]. The value of $\Delta\beta$ required for complete coupling of energy from the top half of the two mode waveguide to the bottom is given by [18]

$$\Delta\beta = \pi/L. \tag{18}$$

$\Delta\beta$ is varied by changing the index of refraction of the waveguiding material in the two-mode section. We will denote the refractive index change, as we did in the last section, as Δn. The change in the difference between the propagation constants of the two modes can then be written as [18]

$$\Delta(\Delta\beta) = \Delta n \, \partial(\Delta\beta)/\partial n. \tag{19}$$

Equating Eqs. (18) and (19) yields [18]

$$\Delta n = (\pi/L)/(\partial(\Delta\beta)/\partial n). \tag{20}$$

In the last section it was shown that for linear EO materials, the refractive index changes proportionally to the applied voltage. With this relation, it can be seen from Eq. (20) that $\partial(\Delta\beta)/\partial n$ is inversely proportional to the applied voltage. $\partial(\Delta\beta)/\partial n$ is also strongly dependent on the waveguide separation s for the directional coupler [18]. Papuchon and Roy [18] showed that as s decreases, $\partial(\Delta\beta)/\partial n$ increases, and as the value of $\partial(\Delta\beta)/\partial n$ increases, the voltage required for switching decreases. Therefore, the maximum value of $\partial(\Delta\beta)/\partial n$ and, thus, the minimum voltage required to switch the coupling guides, occurs when $s = 0$. When $s = 0$, we have a zero-gap directional coupler [18]. Experiments have shown that the value $\partial(\Delta\beta)/\partial n$ varies by an order of magnitude between the conventional directional coupler and the zero-gap directional coupler [18]. This verifies that zero-gap directional couplers require less voltage to switch the coupling than do conventional directional couplers.

Expressions for the power coupling in zero-gap directional couplers are similar to those used for conventional directional couplers. They are given by [29-31]

$$Po_1(l) = Pi_1\cos^2[(\Delta\beta/2 + \Phi o)l] \tag{21}$$

and

$$Po_2(l) = Pi_1\sin^2[(\Delta\beta/2 + \Phi o)l], \tag{22}$$

where Φo is the accumulated, voltage independent phase difference in the phase velocities of the symmetric and antisymmetric modes. With no voltage applied (i.e., $\Delta\beta = 0$), coupling occurs when $\Phi o = \pi/2L$. When enough voltage is applied so that $\Delta\beta = \pi/L$, then complete switching occurs. Equating $\Delta\beta$ with Eq. (15) yields

$$(2\pi/\lambda)(n^3/2)(rV/d) = \pi/L. \tag{23}$$

The voltage required for complete switching is then given by

$$V = (\lambda d)/(n^3 rL), \tag{24}$$

where n is the refractive index of the interaction region. Like the directional coupler, the EO coefficient $r = r_{33}$. By comparing Eq. (24) with Eq. (17), one can see that the voltage required to completely switch the optical input from one channel to the other is less for the zero-gap directional coupler. The zero-gap allows us to treat the center interaction region as one waveguide. Operation of the zero-gap directional coupler switch is illustrated in Fig. 3. Another advantage of zero-gap directional couplers, in addition to operating with less voltage, is that the interaction length is much shorter than the interaction length of conventional directional couplers [5, 11, 12, 24, 32-35]. This results in the reduction of real estate required.

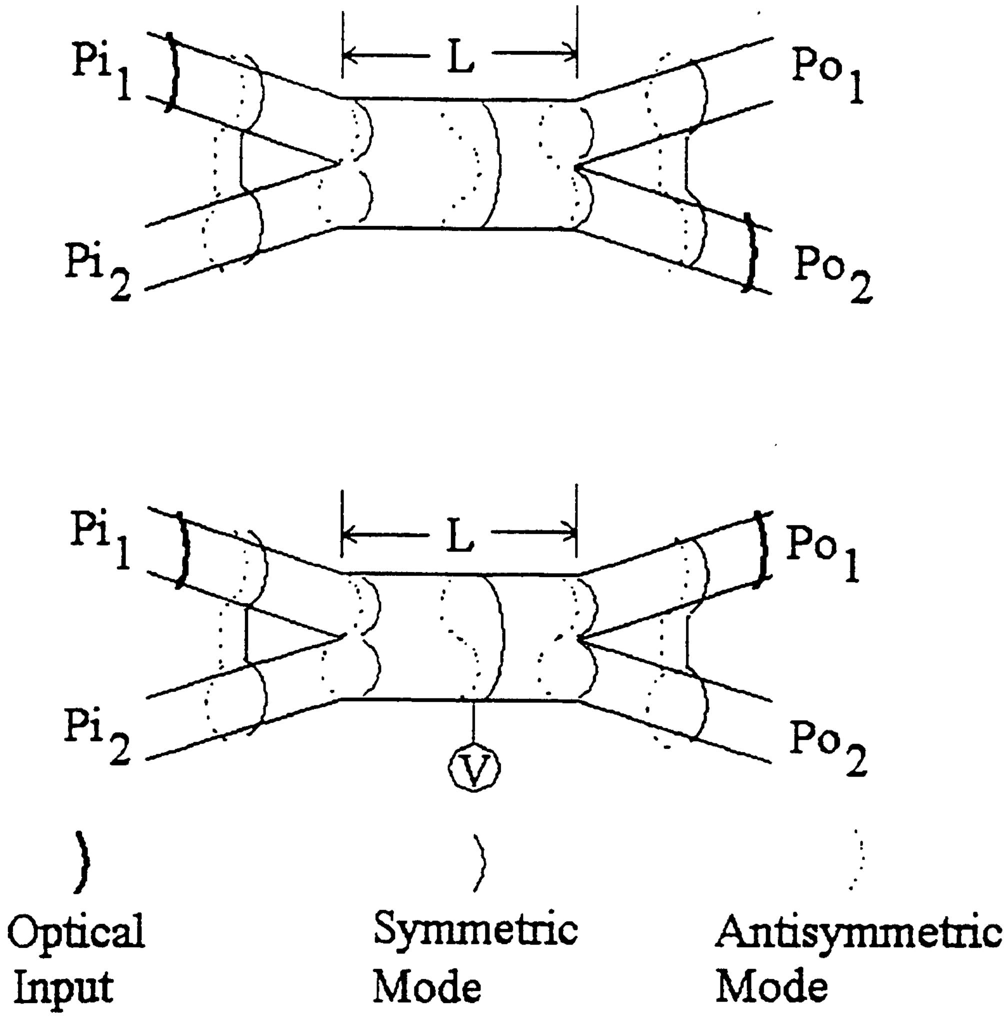

Figure 3. Operation of a Zero-Gap Directional Coupler.

3.2 Wavefront Tilt

An additional parameter which needs to be taken into account for directional couplers and zero-gap directional couplers is wavefront tilt, and its affect on waveguide coupling in the branching section. The larger the tilt angle α of the branching section, the less the waveguide coupling [17]. Tilt introduces phase differences that decrease waveguide interaction in the branching section of waveguide coupling. The maximum allowable tilt angle can be obtained by forcing the branching region of waveguide coupling to be within a single lobe of the standing wave generated by the two waves propagating along the tilted

waveguide portions. This gives the limit [17]

$$\sin(\alpha/2) < \lambda/4nw, \tag{25}$$

where w is the width of the waveguides.

3.3 Interaction Length Of The Directional Coupler

In this section, the interaction length of a directional coupler is determined by substituting the refractive index of the NLO polymer into several dielectric strip waveguide directional coupler models. Driving the separation between the waveguides to zero allows us to determine the interaction length of the zero-gap directional coupler.

Directional coupling is the exchange of power between the guided modes in adjacent parallel waveguides separated by a finite distance. Fig. 4 is a schematic of a conventional directional coupler device. The index of refraction of the core region is n while that of the clad regions is n(1 - Δ). This is less than the index of the core region by an amount Δ. The dimensions a, b and c are, respectively, the width, thickness and separation of the

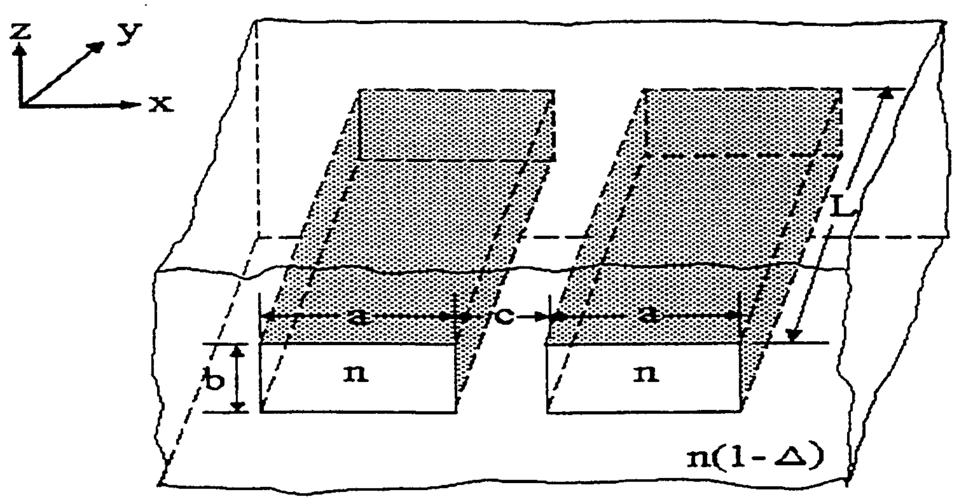

Figure 4. Rectangular Waveguide Directional Coupler.

waveguides. The interaction length, the distance required for total exchange of power from one guide to the other, is L [36]. The wave is assumed to propagate along the y axis.

Extensive treatment of optical waveguide and directional coupler theory has been addressed by many researchers for both continuous two-dimensional film waveguides and dielectric strip waveguides. Various methods, such as dielectric waveguide, coupled mode theory, effective index, beam propagation method and finite-element analysis, have been used [4-6, 8, 10, 11, 20, 37-62]. Analysis of these methods shows good agreement between all of the different models, provided that we are far from cutoff. This means that the normalized frequency, defined as

$$B = (bk/\pi)[n - n(1 - \Delta)]^{1/2}, \tag{26}$$

is greater than or equal to 1.6 for single mode operation [51, 62]. In Eq. (26), the free-space propagation constant of plane waves is defined as $k = 2\pi/\lambda$, or wave number, where λ is the wavelength. Since the waveguides fabricated for this experiment will be rectangular ridge type structures, we will use several of the dielectric strip waveguide methods to model the devices for this experiment [6, 10, 11, 39-46].

3.4 Marcatili Rectangular Dielectric Waveguide Model

In 1969, Marcatili [10] presented analytical models for integrated optical rectangular dielectric waveguides and directional couplers. Fig. 5 illustrates a directional coupler with the following parameters: n_1 and n_2 are the refractive indices of the core and top clad, respectively; n_3 is the refractive index of the outside clad; n_4 is the refractive index of the bottom clad; n_5 is the refractive index of the center clad; the width and thickness of the individual waveguides are a and b, respectively; and the distance of separation between the two waveguides is c. The modes of the dielectric waveguide are classified as transverse electric (TE_{pq}) and transverse magnetic (TM_{pq}) modes. The variables, p = (0,1,2,...) and q = (0,1,2,...), indicate the number of extrema of the electric or magnetic field along the x and z directions, respectively. This gives the order of the mode. For the fundamental "0th order"

TE_{pq} mode, p = q = 0, and the transverse electric mode is given the designation TE_{00}. TE_{pq} (TM_{pq}) modes have the electric field component polarized predominantly in the z (x) direction and the magnetic field component polarized predominantly in the x (z) direction. The amplitudes of the fields have only one maximum in each direction.

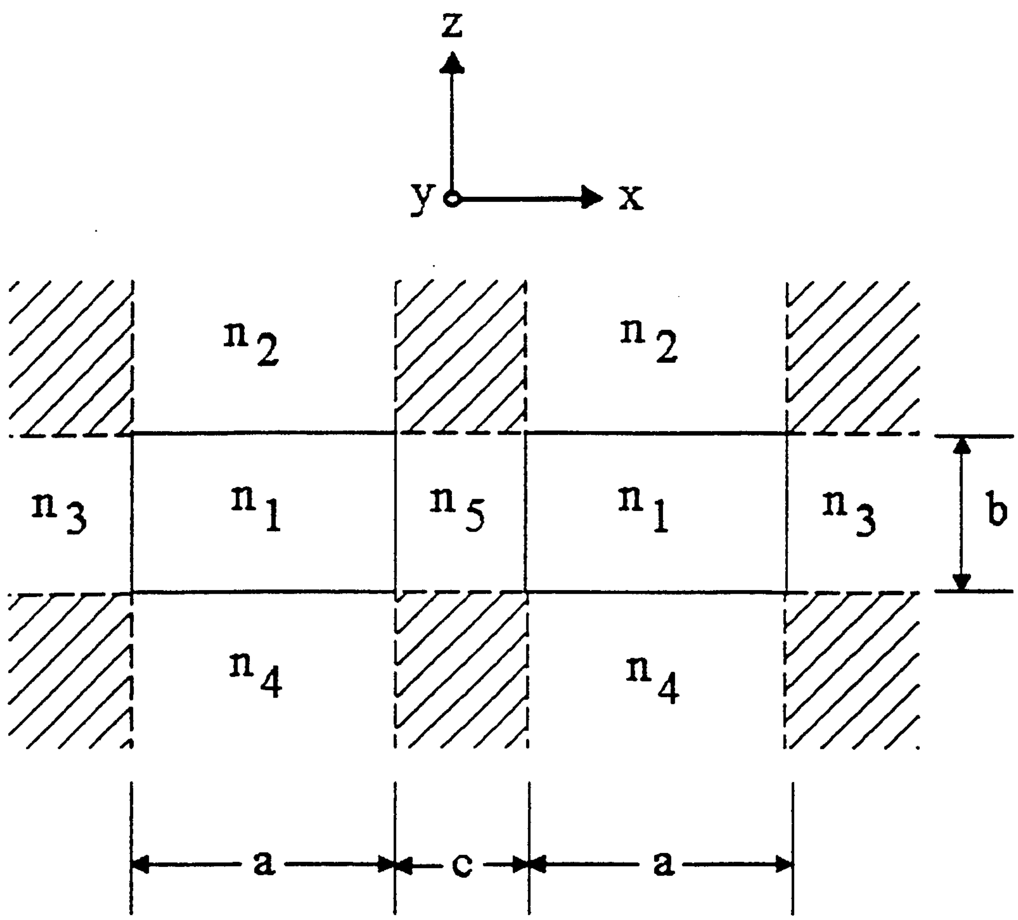

Figure 5. Rectangular Waveguide Directional Coupler Cross Section.

For well-guided modes, the field decays exponentially in the n_2, n_3, n_4 and n_5 regions of the directional coupler waveguide structure. Most of the power travels in the n_1 regions while only a small part of the power travels in the n_2, n_3, n_4 and n_5 regions. An even smaller portion of the power travels in the shaded areas. Marcatili found that very little error was introduced when the fields along the edges of the shaded regions were not properly matched when calculating the fields in the n_1 regions. This allowed him to neglect the shaded areas

from consideration, thus, simplifying the boundary value problem by solving only along the four sides of the core region n_1.

3.4.1 TE_{pq} Modes

For the rectangular dielectric waveguide, illustrated in Fig. 5, the electric and magnetic field components in the five areas are given by [10]

$$H_{x1} = M_1\cos(k_x x + \alpha)\cos(k_z z + \delta)\exp(-ik_y y + i\omega t), \tag{27}$$

$$H_{x2} = M_2\cos(k_x x + \alpha)\exp[-(ik_{z2}z + ik_y y - i\omega t)], \tag{28}$$

$$H_{x3} = M_3\cos(k_z z + \delta)\exp[-(ik_{x3}x + ik_y y - i\omega t)], \tag{29}$$

$$H_{x4} = M_4\cos(k_x x + \alpha)\exp(ik_{z4}z - ik_y y + i\omega t), \tag{30}$$

$$H_{x5} = M_5\cos(k_z z + \delta)\sin(k_{x5}x + \gamma)\exp(-ik_y y + i\omega t), \tag{31}$$

$$H_{z1} = H_{z2} = H_{z3} = H_{z4} = H_{z5} = 0, \tag{32}$$

$$H_{y1} = -[(i/k_y)\partial^2 H_{x1}/\partial x \partial z], \tag{33}$$

$$H_{y2} = -[(i/k_y)\partial^2 H_{x2}/\partial x \partial z], \tag{34}$$

$$H_{y3} = -[(i/k_y)\partial^2 H_{x3}/\partial x \partial z], \tag{35}$$

$$H_{y4} = -[(i/k_y)\partial^2 H_{x4}/\partial x \partial z], \tag{36}$$

$$H_{y5} = -[(i/k_y)\partial^2 H_{x5}/\partial x \partial z], \tag{37}$$

$$E_{x1} = -[(1/(\omega\varepsilon n_1^2 k_y))\partial^2 H_{x1}/\partial x \partial z], \tag{38}$$

$$E_{x2} = -[(1/(\omega\varepsilon n_2^2 k_y))\partial^2 H_{x2}/\partial x \partial z], \tag{39}$$

$$E_{x3} = -[(1/(\omega\varepsilon n_3^2 k_y))\partial^2 H_{x3}/\partial x \partial z], \tag{40}$$

$$E_{x4} = -[(1/(\omega\varepsilon n_4^2 k_y))\partial^2 H_{x4}/\partial x \partial z], \tag{41}$$

$$E_{x5} = -[(1/(\omega\varepsilon n_5^2 k_y))\partial^2 H_{x5}/\partial x \partial z], \tag{42}$$

$$E_{z1} = H_{x1}[(k^2 n_1^2 - k_{z1}^2)/\omega\varepsilon n_1^2 k_y)], \tag{43}$$

$$E_{z2} = H_{x2}[(k^2 n_2^2 - k_{z2}^2)/\omega\varepsilon n_2^2 k_y)], \tag{44}$$

$$E_{z3} = H_{x3}[(k^2 n_3^2 - k_{z3}^2)/\omega\varepsilon n_3^2 k_y)], \tag{45}$$

$$E_{z4} = H_{x4}[(k^2 n_4^2 - k_{z4}^2)/\omega\varepsilon n_4^2 k_y)], \tag{46}$$

$$E_{z5} = H_{x5}[(k^2 n_5^2 - k_{z5}^2)/\omega\varepsilon n_5^2 k_y)], \tag{47}$$

$$E_{y1} = [(i/\omega\varepsilon n_1^2)\partial H_{x1}/\partial z], \tag{48}$$

$$E_{y2} = [(i/\omega\varepsilon n_2^2)\ \partial H_{x2}/\partial z], \tag{49}$$

$$E_{y3} = [(i/\omega\varepsilon n_3^2)\ \partial H_{x3}/\partial z], \tag{50}$$

$$E_{y4} = [(i/\omega\varepsilon n_4^2)\ \partial H_{x4}/\partial z], \tag{51}$$

$$E_{y5} = [(i/\omega\varepsilon n_5^2)\ \partial H_{x5}/\partial z], \tag{52}$$

where $M_{1,2,3,4,5}$ are the amplitudes of the field in each respective medium, α locates the field maxima in the core region n_1, δ locates the field minima in the core region n_1, ω is the angular frequency and ε is the permittivity of free space. The γ term is necessary because single mode operation of a directional coupler will guide two kinds of TE_{00} modes. One is symmetric when $\gamma = 90^{\circ}$, and the other is antisymmetric when $\gamma = 0^{\circ}$ [10]. Both are TEM modes with main field components E_y and H_x. For a symmetric mode, the plane $x = 0$ is a magnetic short circuit. For an antisymmetric mode, the plane $x = 0$ is an electric short circuit. The electric and magnetic field components for both symmetric and antisymmetric modes are depicted in Fig. 6.

The propagation constants k_{xv}, k_y and k_{zv} in each of the five regions are related by [36]

$$k_{xv}^2 + k_y^2 + k_{zv}^2 = \omega^2\varepsilon\mu n_v^2 = k_v^2, \tag{53}$$

where $v = 1, 2, 3, 4, 5$ indicates the region and μ is the permeability of free space. In order to match the fields along the boundaries between the core region n_1 and the top and bottom clad regions (n_2 and n_4) and between the core region n_1 and the outside and center clad regions (n_3 and n_5), Marcatili assumed the following:

$$k_{x1} = k_{x2} = k_{x4} = k_x \tag{54}$$

and

$$k_{z1} = k_{z3} = k_{z5} = k_z. \tag{55}$$

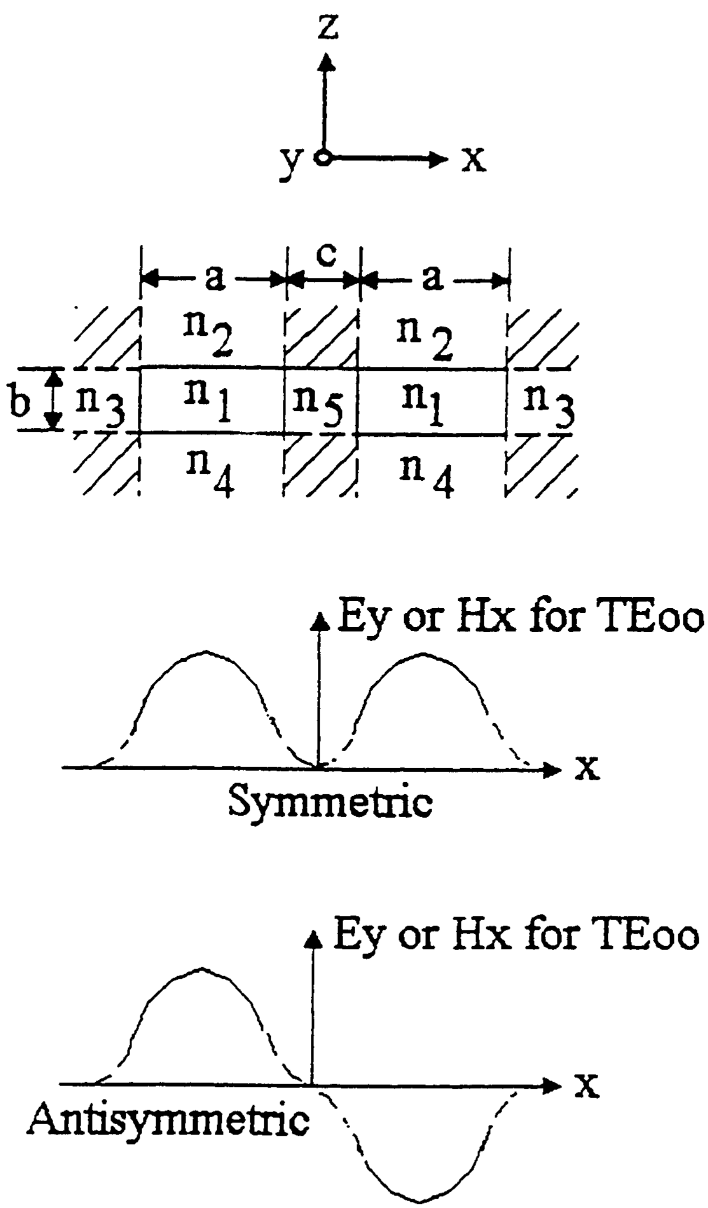

Figure 6. Field Intensity Profiles of the Symmetric and Antisymmetric Modes in a Rectangular Directional Coupler.

Since the refractive index of the core region n_1 is larger than the refractive indices of the cladding regions, only modes of plane wavelets impinging at grazing angles on the surface of the core region n_1 are guided. This implies that $k_x << k_y$ and $k_z << k_y$ and, therefore, the electric field components E_{x1}, E_{x2}, E_{x3}, E_{x4} and E_{x5} can be neglected.

Matching the remaining field components, H_x and E_z, along the boundaries of the core region n_1 gives the transcendental equations [10]

$$k_x a = k_{x0} a[1 + (2\xi_5/a)\exp(-c/\xi_5 - i2\gamma)/(1 + k_{x0}^2\xi_5^2)] \tag{56}$$

and

$$k_z b = (q + 1)\pi - \tan^{-1}[(n_2^2/n_1^2)(k_z\eta_2)] - \tan^{-1}[(n_4^2/n_1^2)(k_z\eta_4)], \tag{57}$$

where the transverse propagation constants k_x and k_z are solutions to Eqs. (56) and (57), respectively. k_{x0} is the solution to [10]

$$k_{x0} a = (p + 1)\pi - \tan^{-1}(k_{x0}\xi_3) - \tan^{-1}(k_{x0}\xi_5). \tag{58}$$

A measure of the penetration depths of the field components in the various media are given by [10]

$$\xi_{3,5} = 1/[(\pi/A_{3,5})^2 - k_{x0}^2]^{1/2} \tag{59}$$

and

$$\eta_{2,4} = 1/[(\pi/A_{2,4})^2 - k_z^2]^{1/2}, \tag{60}$$

where

$$A_{2,3,4,5} = \lambda/[2(n_1^2 - n_{2,3,4,5}^2)^{1/2}] \tag{61}$$

are the maximum thicknesses of the media for which the slab supports only the fundamental TE_{00} mode.

From Eqs. (53) - (55), the axial propagation constant for each mode of the coupler is determined by [10]

$$k_y = (k_1^2 - k_x^2 - k_z^2)^{1/2}, \tag{62}$$

where $k_l = kn_l$ is the propagation constant of a plane wave through a medium with a refractive index n_l at a free-space wavelength λ, and k_x and k_z are obtained from Eqs. (56) and (57).

Substituting γ into Eq. (56) gives slightly different axial propagation constants for the symmetric ($\gamma = 90^\circ$) modes and antisymmetric ($\gamma = 0^\circ$) modes [10].

$$k_{ys} = k_{y0}[1 + 2(k_{x0}^2/k_{y0}^2)(\xi_5/a)\exp(-c/\xi_5)/(1 + k_{x0}^2\xi_5^2)] \tag{63}$$

and

$$k_{ya} = k_{y0}[1 - 2(k_{x0}^2/k_{y0}^2)(\xi_5/a)\exp(-c/\xi_5)/(1 + k_{x0}^2\xi_5^2)], \tag{64}$$

where

$$k_{y0} = (k_l^2 - k_{x0}^2 - k_z^2)^{1/2} \tag{65}$$

is the axial propagation constant of the TE mode of a single dielectric waveguide ($c \to \infty$) (see Fig. 6.).

The interaction length L for total power transfer from one waveguide to the other and the coupling coefficient K between the two waveguides can then be related to k_{ys} and k_{ya} by [10]

$$-iK = \pi/(2L) = (k_{ys} - k_{ya})/2 = 2(k_{x0}^2/k_{y0})(\xi_5/a)\exp(-c/\xi_5)/(1 + k_{x0}^2\xi_5^2). \tag{66}$$

The interaction length and coupling coefficient for the zero-gap directional coupler are obtained by driving the separation between the two adjacent waveguides to zero and substituting the refractive index n_4 for n_5, which yields [24]

$$-iK = \pi/(2L) = 2(k_{x0}^2/k_{y0})(\xi_5/a)/(1 + k_{x0}^2\xi_5^2). \tag{67}$$

3.4.2 TM_{pq} Modes

The analysis for the TM_{pq} modes is very similar to that used for the TE_{pq} modes. The electric and magnetic field components for TM_{pq} modes are found by substituting E for H, H for E, $-\varepsilon$ for μ and $-\mu$ for ε into Eqs. (27) - (52). Following Eqs. (54) and (55), the field components E_{zv} and H_{xv} can be neglected for the TM_{pq} analysis.

Matching the field components, E_x and H_z, along the boundaries of the core region n_1 in the same way as was done to match the field components H_x and E_z for the TE_{pq} analysis gives the transcendental equations [10]

$$k_x a = k_{x0} a[1 + (2\xi_5/a)\exp(-c/\xi_5 - 2i\gamma)/(1 + k_{x0}^2\xi_5^2)] \tag{68}$$

and

$$k_z b = (q + 1)\pi - \tan^{-1}(k_z\eta_2) - \tan^{-1}(k_z\eta_4), \tag{69}$$

where the transverse propagation constants k_x and k_z are solutions to Eqs. (68) and (69), respectively. k_{x0} is the solution to

$$k_{x0} a = (p + 1)\pi - \tan^{-1}[(n_3^2/n_1^2)(k_{x0}\xi_3)] - \tan^{-1}[(n_5^2/n_1^2)(k_{x0}\xi_5)]. \tag{70}$$

η_2, η_4, ξ_3 and ξ_5 are obtained from Eqs. (59) - (61).

The interaction length L for total power transfer from one waveguide to the other and the coupling coefficient K between the two waveguides are determined by Eq. (66) using k_{y0}, k_z and k_{x0} obtained from Eqs. (65), (69) and (70), respectively. The interaction length and coupling coefficient for the zero-gap directional coupler are obtained by substituting k_{y0}, k_z and k_{x0}, obtained from Eqs. (65), (69) and (70), into Eq. (67) [24].

Marcuse [11] derived a rectangular dielectric waveguide model following the approach developed by Marcatili. It is also widely used and gives identical results.

3.4.3 Alternative Models

In a 1975 paper, Bums and Milton discussed mode conversion in planar dielectric separating waveguides [39]. This has since become known as the effective index method, and is treated in detail by Nishihara, Haruna and Suhara for both two and three-dimensional dielectric waveguide structures [6]. The effective index method is based on the concept of the effective index of the guided mode.

In 1976, Fleck, Morris and Felt proposed a propagating beam method (bpm) for computing fields of an optical beam passing through a medium [51]. The beam propagation method is derived for a scalar field. The theory is restricted to small changes in the refractive index. The method calculates the characteristics of an input beam as it propagates through a medium over a small distance y, and then corrects for the variations of the refractive index as seen by the beam over this distance y. It has already been applied to several optical fiber and integrated optic applications [41-47, 54, 60, 61].

3.4.3.1 The Computer Program BeamPROP

The BeamPROP software incorporates advanced finite-difference beam propagation techniques for simulation, and a modem graphical user interface for case of circuit layout and analysis. The benefit of good design and modeling tools is well known in the electronics industry, where both device and circuit simulation programs, such as PISCES and SPICE, have been instrumental in advancing the availability and use of integrated electronic circuits. BeamPROP brings this important capability to the photonics area, and can be an extremely useful tool for research and development groups in both university and industrial environments.

The main program contains a complete CAD layout system for design of waveguide devices and circuits, and controls simulation features such as numerical parameters, input field, and display and analysis options. The simulation program, which can be executed within the main program or as a standalone, performs the actual

simulation and provides a graphical display of the field and other quantities of interest for analysis.

The CAD system was designed specifically for photonic circuits, and incorporates a natural, object-oriented input model. Several unique features such as user programmable circuits and optical pathways and monitors allow for rapid parameter variation and ease of analysis. The CAD system allows a smooth transition to the simulation program, with quick startup and easy access to features. The program provides intelligent choices for default numerical parameters, which are problem-dependent. The simulation incorporates integrated, real-time analysis and display of the simulation results, and can be run in the background. Both 2D (one transverse, one longitudinal) and 3D (two transverse, one longitudinal) simulation techniques are available.

The software, BeamPROP, was developed at Columbia University and licensed in 1994 to RSoft, Inc., a commercial software firm. The software is capable of addressing such problems as:

- Fiber to waveguide coupling
- Source to waveguide and waveguide to detector coupling
- Waveguide transitions
- Bend and routing analysis
- Transmission/loss calculation
- Signal-to-noise, modal noise, and BER estimation

3.4.3.2 Theoretical Background

The objective of BeamPROP is to provide a general simulation package for computing the propagation of light waves in arbitrary waveguide geometries. This is a complex problem, in general, and several assumptions are made at the outset (many of which are subsequently relaxed). We first limit our attention to monochromatic scalar

waves, which are described by the Helmholtz equation:

$$\nabla^2\phi + \frac{\omega^2}{c^2}n^2\phi = 0 \tag{71}$$

Here, the optical field (one component of E or H) has been written as ϕ (x,y,z) e^{-ikt} where ϕ is the angular frequency of the light. The refractive index distribution in the domain of interest is assumed to be given by n(x,y,z), and is determined by the geometry of the waveguide circuit.

The BeamPROP software determines an approximate solution to the above equation using several techniques. The computational core of the program is based on a finite difference beam propagation method as described in the paper by R. Scarinozzino and R.M. Osgood, Jr. [63], and references therein. This technique uses finite difference methods to solve the well-known parabolic or paraxial approximation of the Helmholtz equation, which is written as:

$$2i\bar{k}u_z + \nabla_T^2 u + \left(\bar{k}^2 - k^2\right)u = 0 \tag{72}$$

In this equation we have assumed that the wave is propagating primarily along z, and have factored out the rapid variation in the field by writing $\phi(x, y, z) = u(x, y, z)\, e^{ikz}$, where k is a constant representing the characteristic wavenumber for the propagation. We denote the wavenumber in free space by $k_o = \omega / c = 2\pi/\lambda$, and have introduced the notation $k(x, y, z) = k_o n(x, y, z)$ to represent the spatially dependent wavenumber. The above equation is solved numerically using an implicit finite difference scheme as described in reference 1. In addition, the program uses "transparent" boundary conditions following the work of G.R. Hadley [64].

The fundamental physical limitation of the above approach results from the parabolic approximation to the Helmholtz equation, which implies a paraxiality condition on the primary direction of propagation. These limitations can be reduced using more accurate approximations to the Helniholtz equation as outlined by G.R. Hadley [36].

BeamPROP has the option of implementing this technique, and includes (1,O), (1, 1), (2,2), (3,3), and (4,4) Pade approximations.

BeamPROP utilizes vector beam propagation techniques to overcome the limitations of the assumption of scalar waves which prevents polarization effects from being considered. Those methods are based in part on the approach described by W.P. Huang and C.L. Xu [65, 66] and related references.

BeamPROP uses a bidirectional beam propagation (BPM) algorithim. The algorithim considers coupled forward and backward traveling waves, and can account for reflection phenomenon, including resonant effects as found in grating structures.

The physical propagation problem requires two key pieces of information:

1. The refractive index distribution, $n(x, v, z)$.
2. The input wave field, $u(x, y, z = 0)$.

From these, the physics dictate the wave field throughout the rest of the domain, $u(x, y, z > 0)$. The software provides a way to specify this information.

The solution algorithm requires additional input in the form of numerical simulation parameters such as:

1. A finite computational domain $\{x \in (x_{min}, x_{max})\}$, $\{y \in (y_{min}, y_{max})\}$, and $\{z \in (z_{min}, z_{max})\}$.

2. The transverse grid sizes, ∇x and ∇y.

3. The longitudinal step size, ∇z.

The software attempts to estimate appropriate values for these parameters, but allows the user to override them. As with any simulation, confidence in the accuracy of the numerical solution requires experimentation to determine the sensitivity to the numerical parameters.

3.5 Refractive Index of the Waveguide Cladding

The refractive index of the cladding layer can be found using the relation [12]

$$n_{core} - n_{clad} > m^2\lambda^2/[4(t_g)^2(n_{core} + n_{clad})], \tag{73}$$

where m is the mode number and t. is the thickness of the core. Assuming single mode operation (m=1), Eq. (73) becomes

$$n_{clad} > [(n_{core})^2 - \lambda^2/[4(t_g)^2]^{1/2}. \tag{74}$$

One can also use a TE/TM mode analysis presented by Ghatak, Thyagarajan and Shenoy [65] to model the loss for a given mode.

The refractive indices and EO coefficients for the various polymers are usually provided by the manufacturer, but they can also be determined experimentally. Now that the basic theory for designing EO devices has been presented, one can address fabrication issues.

3.6 Device Fabrication

NLO polymers typically come in crystal or powdered form. For our example, we will use an NLO polymer from AdTech Systems Research known as LD-3 [129]. It is composed of a methymethacrylate (MMA) polymer containing 4-[bis (2-hydroxyethyl) amino]-4'- ((6-methacryloyl-hexyl) sulfonyl) azobenzene nonlinear optical chromophores. A recipe for reconstituting the polymer into a liquid for spin casting is usually provided by the polymer manufacturer. We will start with LD-3 in powder form. First, grind 0.10 grams of LD-3 into a fine powder and dissolve the powder in 1.0-1.5 ml of pure and dry organic solvent tetrahydrofurane (THF) [129]. Add 0.060 grams of cross-linker 4,4'-diisocyanato-3,3'dimethoxybiphenyl, which forms 3D networks and locks the dipole aligned chromophores [129]. Stir the mixture for 15 minutes at room temperature. Filter the mixture through a 0.2 μm syringe filter [129]. With the material in its liquid form we are ready to begin fabrication of our EO device. There are several methods that have been employed for fabricating NLO polymer devices. The two most common techniques, namely photobleach [35, 67-71, 73, 78-94] and etch-and-fill [35, 68-70, 72-81] are described below in 3.6.1 and 3.6.2.

3.6.1 Photobleach

To begin device processing, we evaporate a thin metal layer on top of a substrate, which can either be glass, polymer or semiconductor. This metal layer will be the ground plane electrode. It can be gold, aluminum, titanium/tungsten/gold or any good conductor; it should be 4000 Å - 1 μm thick for good conductivity. Deposit a passive polymer bottom cladding material with a refractive index about 0.02-0.04 less than that of the core. The cladding material is usually synthesized to work with the NLO polymer being used. It can be an acrylate, polyimide, or polyetherimide, just to name a few. It must also have a higher glass transition temperature (Tg) than the core material in order to perform the poling step. It is spin cast over the metal layer at an acceleration and a speed to yield a thickness of 3 μm. The cladding layer is then cured by baking on a hot plate until dry. The exact time depends on the type of polymer used. The NLO polymer core layer is then deposited on top

of the cladding layer at an acceleration and speed in order to yield a thickness of 2 μm. It is baked until dry. A passive polymer top cladding layer is deposited in the same manner in order to yield the same thickness as the bottom cladding layer. The top cladding layer is also baked until it is dry. A second metal layer, used for waveguide patterning, is evaporated on top of the top cladding layer. It is a good conductor, typically 500 Å thick. The metal layer is then patterned with the desired EO waveguide circuit, using standard lithographic techniques, leaving a metal mask. The wafer is then flood exposed with ultraviolet (UV) light. Exposure to UV results in a slight and very controllable reduction in the refractive index of the NLO polymer. This process is called photobleach. Photobleaching defines the side cladding layers of the channel waveguide. Exposures take several hours, and the refractive index of the side cladding can be controlled to the 4th decimal place. The metal mask used for photobleaching is then stripped off. A third 500-3000 Å metal layer for the electrodes is evaporated on top of the top clad. The top metal layer is patterned with the desired electrode structure using standard IC tools and techniques. After the electrodes have been patterned, the NLO material directly under the electrodes needs to be poled in order to operate as an EO device. Poling is a technique used to align the molecules or moieties of the material in order to maximize the EO properties of the NLO polymer. Poling is performed by heating the EO circuit to a temperature above the glass transition temperature of the material, specified by the manufacturer, and then applying a DC voltage. The higher temperature allows the molecules within the material to move freely. For the NLO polymer LD-3, a poling temperature of 150°C is specified. An electric field is then applied across the electrodes using soft tip probes. The moieties will align in the direction of the electric field, thus, increasing the electro-optic coefficient r_{33} in those regions. The poling voltage is typically 150 VDC/μm. Thus, for this example, the poling voltage required would be 1200 VDC [35, 66-72, 76-81, 83-85, 87-96]. With the voltage still applied, the circuit is cooled to room temperature. This locks the moieties in place. This type of poling is known as selective poling [67-71, 78-94, 97]; only the NLO material under the electrode is poled. Since the regions along the axis parallel to the applied voltage become birefringent, the electric field of a TM mode will see a higher refractive index in the poled regions than in the un-poled regions, becoming waveguides for TM light [93].

The device is now ready for operation. The parameters for poling and photobleaching are different for the various NLO polymers; one needs to determine optimum conditions through experimentation. The separation between the electrodes for this example is 8 μm. The thicknesses for the cladding and core layers given above have been determined, by several researchers, to provide low propagation loss and are the thicknesses generally used [66-80, 82-96, 98]. However, an 8 μm separation between electrodes renders long devices not suitable for MCM applications [35]. This will be addressed in a later.

3.6.2 Etch and Fill

For etch and fill, we once again begin by depositing metal onto a substrate for the ground plane. A 5 μm passive polymer cladding layer is spin cast over the metal and heated until dry. Next, the waveguide circuit is patterned onto the cladding layer using standard IC tools and techniques. 2 μm of the cladding layer are etched using either wet or dry etch processes. The NLO polymer is spin cast onto the circuit filling the etched regions and cured by heating. A 3 μm passive polymer cladding layer is spin cast on top of the NLO polymer core layer and cured. Metal is deposited and patterned to provide electrodes over the switching regions. The device is then poled. The difference between the two techniques is that the refractive indices of the passive polymer side cladding layers cannot be controlled as precisely as the refractive indices of the photobleached NLO polymer side cladding layers. This can be important when a precise interaction length L is desired. However, the etch and fill method does eliminate a metalization, patterning and exposure step required for the photobleach method.

3.6.3 Corona Poling

A poling method commonly used is known as corona poling [67-71, 82]. After the spin cast films are vacuum dried and heated to 150°C, a small probe tip emitting a high electric field, typically about 5 KVDC, is positioned 2.0 cm over the heated NLO polymer. This provides the 150 VDC/μm poling voltage. The 150°C temperature and 5 KVDC

poling voltage are maintained for 2 hours. The films are cooled to room temperature, with the electric field still applied. When the films reach room temperature, the voltage can be turned off, and the material is ready for EO device fabrication. The switching electrodes then need to be deposited and patterned. Corona poling is also attractive for material characterization because the NLO polymer can be poled over a large area. For device fabrication, however, care must be taken to deposit the NLO material only in the switching region, when using corona poling. Since a poled NLO polymer exhibits higher propagation loss than the un-poled NLO polymer [69-71, 82], an EO circuit fabricated using this method will exhibit higher loss if the NLO material is deposited anywhere besides the switching region.

4. PRACTICAL NONLINEAR OPTICAL POLYMER ELECTRO-OPTIC DEVICES

Electro-optic modulators and directional couplers using NLO polymers have been modelled, fabricated and/or analyzed extensively over the years by many researchers [35, 66-72, 83-85, 97]. The EO coefficients for various NLO polymers have been measured by several researchers as well [69-70 73-82, 86-92, 97-103].

However, even with the excellent material characteristics that have been demonstrated, several barriers have prevented NLO polymers from progressing much further than being used for research devices. One of these barriers is poling voltage. In order to align the moieties to attain the nonlinearity of the material, one needs to pole the polymer with a high voltage. As stated earlier, the level of this poling voltage can be 1200 VDC or greater. Voltage levels of these magnitudes prevent the ease of integration of optics with electronics. Lift-off techniques are being pursued to allow for integration, but such techniques add to the fabrication cost and can defeat the simplicity claimed for NLO polymer device fabrication. An electronics company that does not utilize lift-off in their current fabrication, might be reluctant to introduce it into their process, unless there were a significant and marketable performance enhancement.

For compatibility with electronic processes, including solder baths, NLO polymers need to be able to retain their nonlinearity at high temperatures. It has been demonstrated that the higher the poling retention temperature stability, the lower the nonlinearity of the material [67, 70, 82]. However, one would like to achieve a high nonlinearity for the material; this is its most attractive characteristic. Due to high poling voltages and lower nonlinearities caused by rugedization, one should consider using these materials in stand alone EO devices. There is no immediate requirement to monolithically integrate with electronics and/or electronic fabrication processes. This will allow for the relaxation of the high temperature stability requirement, and it will provide a polymer with a higher EO coefficient. It is the belief of this author that for the near term, it is more important to get a

competitive NLO polymer device into the market than to focus on integration with electronics.

4.1 Electrode Separation

Substituting the properties of the various competing materials into a zero-gap directional coupler (ZGDC), as described in Chapters 4.3, gives one a good material comparison. These are presented in Table 1. Looking at Table 1, it is clear that the NLO polymer is not being utilized to its full potential. If one could find a way to reduce the electrode separation for NLO polymer devices, the switching voltage could be reduced. For $d = 1\ \mu m$, using the above parameters, $L = 1.5$ mm and the voltage-length is reduced to 7.5 V-mm. Thus, a ZGDC, using the NLO polymers that are currently available, has the potential of having the lowest switching voltage of any integrated optic EO device demonstrated to date. Table 2 illustrates the potential of decreasing the electrode separation. Looking at Table 2, it can be seen that the potential exists to realize extremely short devices.

Table 1. NLO Materials Comparison [24, 32-35, 66-68, 72, 73, 77, 83-86, 99, 100, 104-119].

Material	V_π	λ	n	r_{33}	d	L (mm)	Voltage-Length
Bulk III-V Semiconductor	5 V	830 nm	3.42	1.5 pm/V	2 μm	5.6 mm	28 V-mm
$LiNbO_3$	5 V	830 nm	2.2	32 pm/V	9 μm	4.4 mm	22 V-mm
MQW III-V Semiconductor	5 V	830 nm	3.42	4.7 pm/V	2 μm	1.8 mm	9 V-mm
NLO Polymer	5 V	830 nm	1.63	26 pm/V	8 μm	12 mm	60 V-mm

Table 2. NLO Polymer Comparison [35]

Tolerable Loss	V_π	λ	n	r_{33}	d	L (mm)	Voltage-Length
12 dB/cm	5 V	830 nm	1.63	26 pm/V	1 μm	1.5 mm	7.5 V-mm
21 dB/cm	5 V	830 nm	1.63	45 pm/V	1 μm	0.85 mm	4.3 V-mm
187 dB/cm	5 V	830 nm	1.63	400 pm/V	1 μm	96 μm	0.5 V-mm

As a first option, one could decrease the core thickness from 2 μm to 1 μm. Doing this would allow for a 1 μm reduction in the separation between electrodes. However, this would only offer a slight reduction in the switching voltage. In order to reduce the electrode separation any further, one would have to either reduce the thickness of the cladding layers or, as in our proposal, render the cladding layers conductive. Several researchers have recently increased the conductivity of the cladding layers in order to pole the core layer in the triple stack polymer device configuration to its full NLO value [67, 71, 83, 86, 91, 92, 94, 97]. This level of conductivity is not adequate enough to allow the cladding layers to act as switching electrodes. By using conductive polymers, on the other hand, such as HCl doped polyanilene, AsF_5 doped polyacetylene or doped polypyrrole, conductivities of 2×10^2 S/cm to 1×10^5 S/cm can be realized [120-124]. The conductivity of polyanilene is within a factor of 300 of copper. The conductivity of polyacetylene is within a factor of 6 of copper.

Increasing the conductivity of the cladding layers to these conductivity levels, however, increases the dielectric constant of the material. This may produce significant propagation loss [56, 57]. It has been demonstrated, at $\lambda = 632$ nm, that undoped, non-conductive polyanilene, has a dielectric constant $\varepsilon = 8.47 + 1.14i$ and conductive, HCl doped polyanilene has a dielectric constant $\varepsilon = 13.4 + 2.85i$ [57]. The loss incurred by rendering the cladding material highly conductive may prove too high for practical device operation. One might, therefore, consider a thin charge sheet (< 0.1 μm) of conductive

polymer spin casted between the core and cladding layers. This would undoubtedly increase propagation loss, but, not, one would hope, to the levels anticipated from using conductive cladding layers. Fig. 7 is a schematic illustrating the stacked structure under consideration.

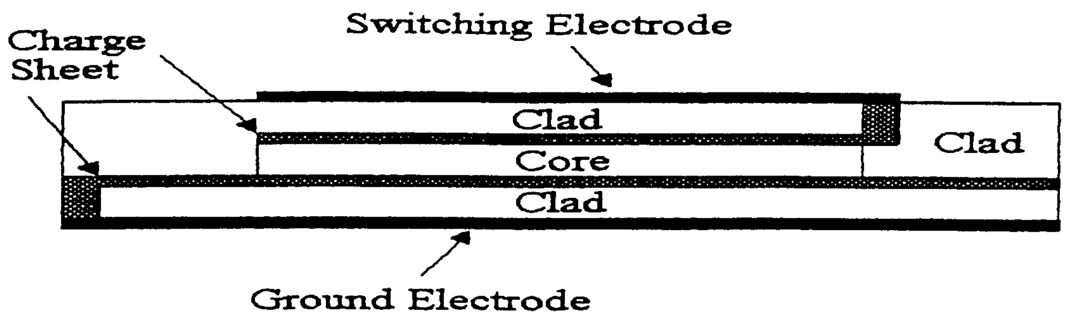

Figure 7. Schematic of Triple Stack Including Conductive Polymer Charge Sheets [35].

4.2 Passive Zero-Gap Directional Coupler

We will first analyze our scheme for the passive device (no voltage applied). In anticipation of the higher losses due to the conductive polymer, we would only want to use the NLO polymer for the interaction region of the switch. The input/output channels, as well as the general routing, should be fabricated using a passive polymer, such as General Electric polyetherimide (ULTEM). It has demonstrated losses of 0.24 dB/cm at $\lambda = 830$ nm [106, 125]. Limiting the NLO polymer to the interaction channel of the device only allows one to relax the current low loss requirement for NLO polymers. Fig. 8 is a schematic of the passive zero-gap directional coupler under investigation, with the active polymer making up the interaction region and a passive polymer making up the input/output channels. By using the waveguide and material parameters given in Table 1 and substituting d = 1 μm, the predicted optimum interaction length (L) for the passive ZGDC is only 101 μm. Fig. 9 is a BeamPROP beam propagation model representation of this device.

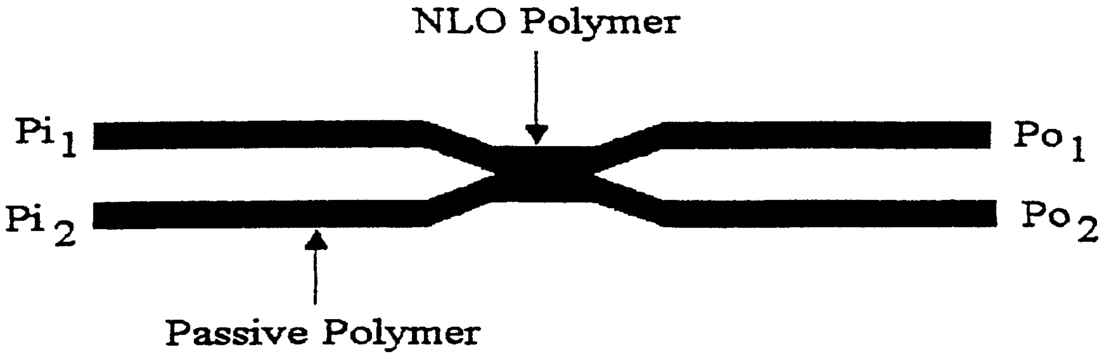

Figure 8. Schematic of a Passive Zero-Gap Directional Coupler With an NLO Polymer Interaction Region and Passive Polymer Input/Output Channels [35].

In addition, the accuracy of the width of the channels for a ZGDC is not too critical. If we can control the accuracy of the width of the interaction channel to within 0.1 μm, which is the current tolerance for standard IC fabrication tools, L will only change by 7.6 μm. We would be able to control the coupling to within 93% of complete coupling. This would prove very fabrication tolerant.

For our ZGDC, we are also assuming that we will be able to match the refractive indices of the NLO polymer and the passive polymer to within 0.01. Calculating the percentage of coupling with this amount of index tolerance predicts that we could control the coupling to within 93% of complete coupling. This, again, proves very fabrication tolerant. In order to implement this type of structure, we would have to utilize the etch and fill technique. However, with such a fabrication tolerant device, one does not require the precise refractive index control that can be achieved using photobleach. Fig. 10 is a BPM of the device behavior, including the 0.01 refractive index mismatch. Assuming 1.8 dB total loss for this device, corresponding to 1.5 dB/cm propagation loss for the conventional 12 mm long device allows one to tolerate a propagation loss of 178 dB/cm for the 101 μm passive ZGDC.

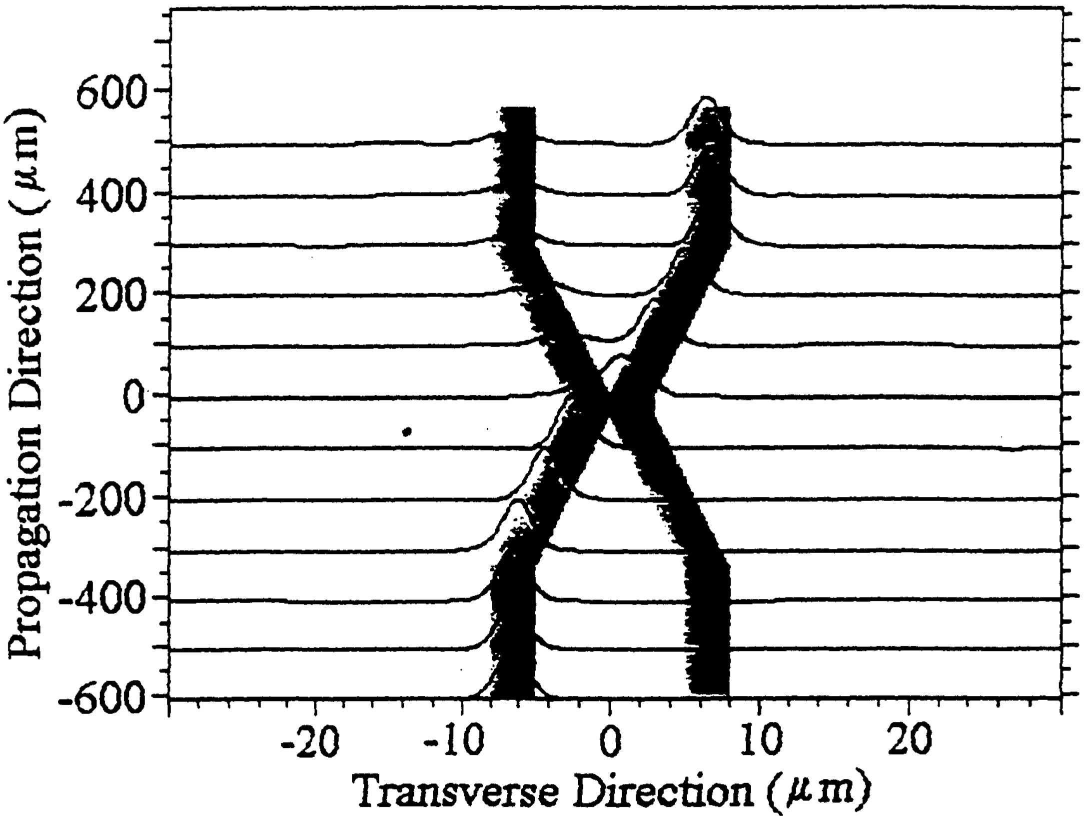

Figure 9. Beam Propagation Model of Passive Zero-Gap Directional Coupler Using NLO and Passive Polymers With Matching Indices.

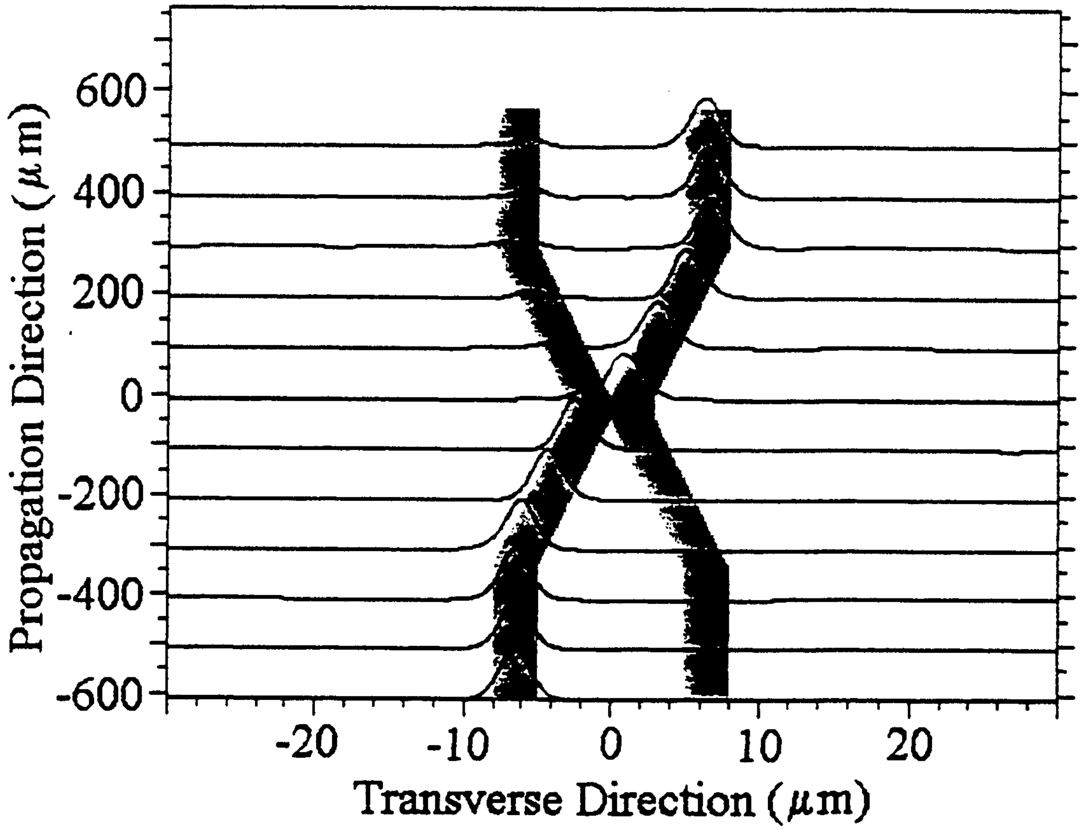

Figure 10. Beam Propagation Model of Passive Zero-Gap Directional Coupler Using NLO and Passive Polymers With 0.01 Mismatched Indices.

4.3 Active Zero-Gap Directional Coupler

For switching, we need to implement the active device (voltage applied). In order to keep the switching voltage to a minimum, the active ZGDC will require a longer interaction length than the passive device. The coupling will also be harder to predict, since any error in index matching or width accuracy will be multiplied by a factor determined by dividing the realized active device length by the optimum passive device length. For the active device case, when using the parameters from Table 1 along with d = 1 μm and a 0.01 refractive index difference between the NLO and passive material, our coupling error is still very low. Fig. 11 is a BPM of the behavior of the active ZGDC with perfect index match. Fig. 12 is a BPM of the active ZGDC with 0.01 index mismatch.

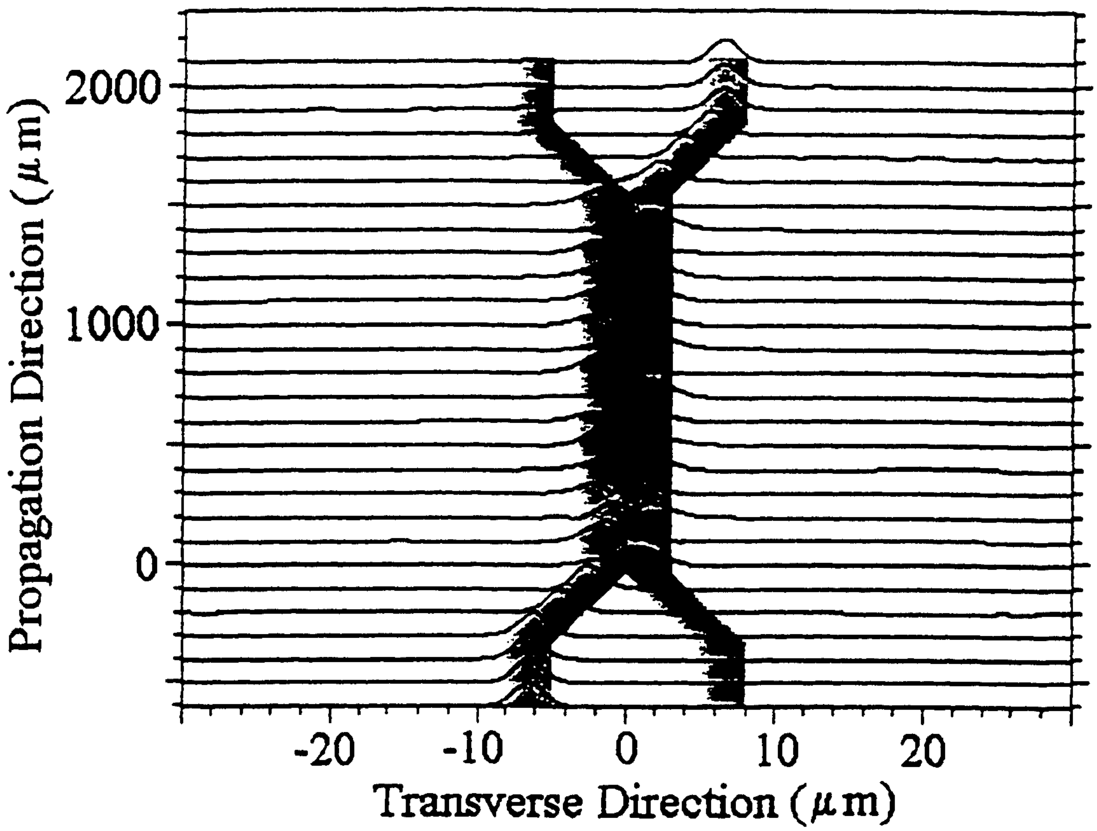

Figure 11. Beam Propagation Model of Active Zero-Gap Directional Coupler Using NLO and Passive Polymers With Matching Indices.

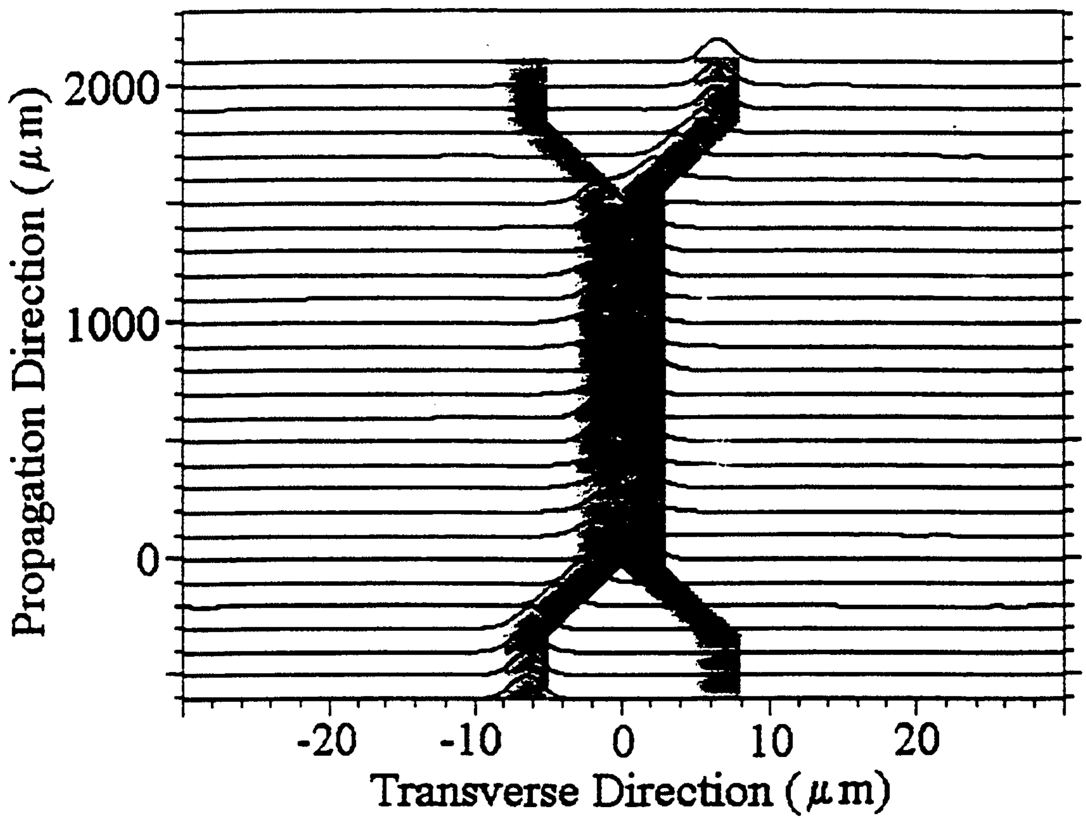

Figure 12. Beam Propagation Model of Active Zero-Gap Directional Coupler Using NLO and Passive Polymers With 0.01 Mismatched Indices.

We would anticipate the coupling to be more difficult to predict when fabricating the actual device, and we would expect the active device to be less fabrication tolerant than the passive device. However, since we will be applying a voltage for switching anyway, we should be able to simply apply a voltage to null the device in the complete coupling state. In any case, this 1.5 mm long device would have the potential for realizing 7.5 V-mm switching. This is a significant benefit, which would offset the inconvenience of having to null the device. Low loss requirements for current NLO polymers could also be relaxed for the active ZGDC. Assuming a 1.8 dB total loss for this device, the same as we did for the passive ZGDC, would allow us to tolerate a propagation loss of 12 dB/cm for the 1.5 mm active ZGDC.

Hence, this length would be short enough to conceivably build an array NLO polymer EO devices within a small chip for placement within a multichip module.

4.4 Nonlinear Polymer to Passive Polymer Coupling

Another important issue to be addressed is the coupling efficiency between the NLO polymer material and the passive polymer material. If we wish to use the NLO polymer for the EO device and the passive polymer for the general routing, in order to minimize propagation loss, we need to conceive better coupling techniques than the current butt coupling technique. Butt coupling two waveguides together has proven very lossy, especially between two materials of different refractive indices. It is not efficient enough for coupling the NLO material with the passive material. One possible method may involve tapering the two materials together or blending the two materials. Another may be to utilize the passive zero-gap directional coupler or to use grating couplers. In any event, in order for NLO polymer devices to become practical and competitive for computer applications, good coupling efficiency needs to be achieved.

4.5 Conductive Cladding

AFRL has demonstrated [126] an increase of up to 13 times the effective electro-optic (EO) coefficient of electrode poled nonlinear optical polymers using a polyethylene dioxythiophene (PEDOT) based conductive polymer cladding, compared to using passive polymer claddings. We have also demonstrated the lowest poling voltage to date, 300 V, for an asymmetric NLO waveguide structure with 2 μm thick core and 2 μm thick claddings. This is 3 orders of magnitude less than other NLO polymer waveguide optoelectronic devices that are electrode poled for the maximum EO coefficient. Since the cladding material is more conductive than the core material, the majority of the applied poling voltage is dropped across the core, realizing a higher EO coefficient than for a conventional device using a passive polymer cladding. The technique has the potential for in situ poling because of the lower voltage. In addition, the electrical dielectric constant of the PEDOT based polymer was measured to be an order of magnitude higher than that of the NLO polymer core that was used when measured at 100 KHz, thus dropping 40% more of the applied voltage across the core, at that

frequency, than when using a nonconductiv polymer cladding. These results show promise for shorter, lower operating voltage devices.

5.0 EXPERIMENTAL RESULTS

Two sets of samples of AdTech Systems Research's NLO polymer LD-3 were evaluated at the University of Southern California (USC) [127]. The first set of tests involved 200 samples. From that set an E-O coefficient of 11 picometers per volt (pm/V) was found when measured at a 1 micrometer wavelength [128]. The highest coefficient found in the second set was 5 pm/V when measured at a 1 micrometer wavelength. The USC samples were corona poled. The USC measurements were made using the attenuated total reflection technique. The first USC test set, only a few of the samples had a high coefficient.

Samples were also measured at AFRL/MLPO [127]. Those samples were measured at a 780 manometer (nm) wavelength. The samples were poled using the electrode poling technique. The highest E-0 coefficient found was 5 pm/V. The AFRL/MLPO measurements were made by the Teng Man technique. The AdTech polymer is based on a dye and at 780 nm the E-O coefficient should have been 19 pm/V. That value arises because of the dispersion of the medium.

6. CONCLUSIONS

It was concluded that the chemical composition by the AdTech polymer fabrication was not adequately controlled. Further, other nonlinear polymer sources have been found at other organizations that offer promise.

LD-3 material did not posses the necessary E-O coefficient as set by CRDA agreement. It was on that basis it was decided to terminate the CRDA effort between AFRL/SNDI and AdTech on 1 May 2000.

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APPENDIX

The Appendix consists of copies of the two patents granted for conductive cladding of rectangular waveguides. The two patents are:

US Patent # 5,887,116 granted March 23, 1999 (See pages A1-A11).

US Patent # 5,892,859 granted April 6, 1999 (See pages A13 - A26).

US005887116A

United States Patent [19]

Grote

[11] Patent Number: 5,887,116

[45] Date of Patent: Mar. 23, 1999

[54] INTEGRATED CIRCUIT COMPATIBLE ELECTRO-OPTIC DEVICE USING CONDUCTIVE POLYMER CLADDING LAYERS

[75] Inventor: James G. Grote, Yellow Springs, Ohio

[73] Assignee: The United States of America as represented by the Secretary of the Air Force, Washington, D.C.

[21] Appl. No.: 872,898

[22] Filed: Jun. 11, 1997

[51] Int. Cl.[6] G02B 6/10

[52] U.S. Cl. 385/2; 385/122; 385/8; 385/16; 385/131

[58] Field of Search 349/196, 197; 385/2, 122, 129, 130, 131, 8, 16

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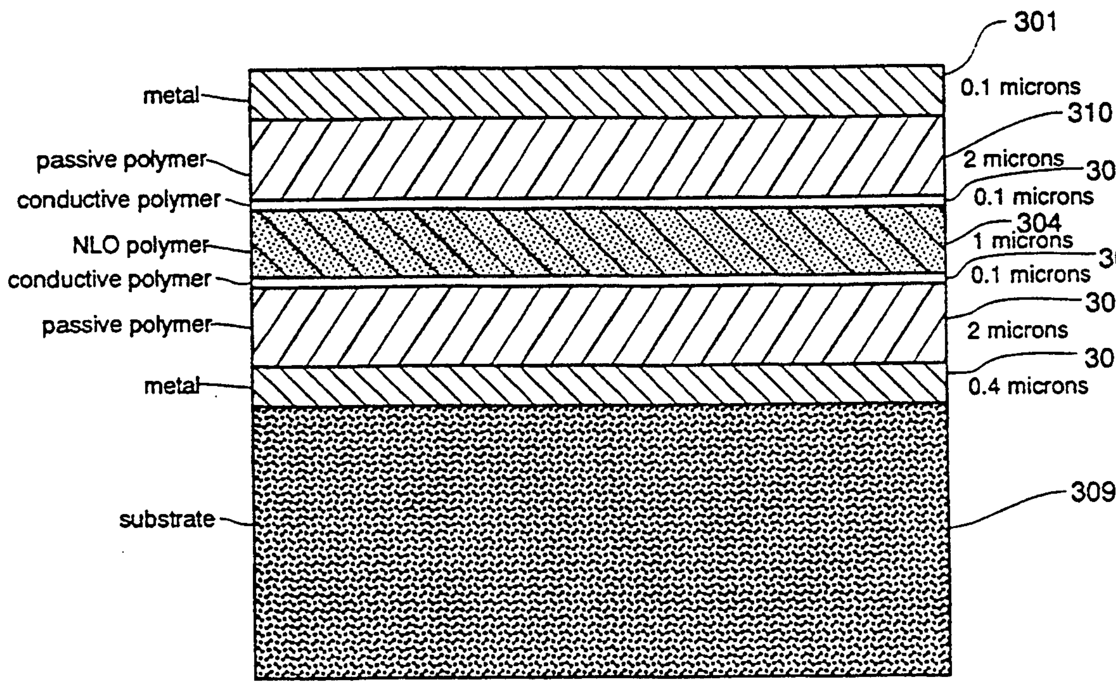
Attorney, Agent, or Firm—Gina S. Tollefson; Gerald B. Hollins

[57] ABSTRACT

A commercially attractive arrangement for monolithic integration of a nonlinear optical polymer transverse electro-optic device on an electronic integrated circuit chip. The invention provides for conductive polymer cladding layers immediately adjacent to an optical signal transmitting non-linear optical polymer core layer. The cladding layers result in a reduced core layer poling voltage, reduced device length, and 5 VDC or less controlling voltage, allowing inclusion into electronic integrated circuit chips of a size compatible with multichip module integration.

10 Claims, 6 Drawing Sheets



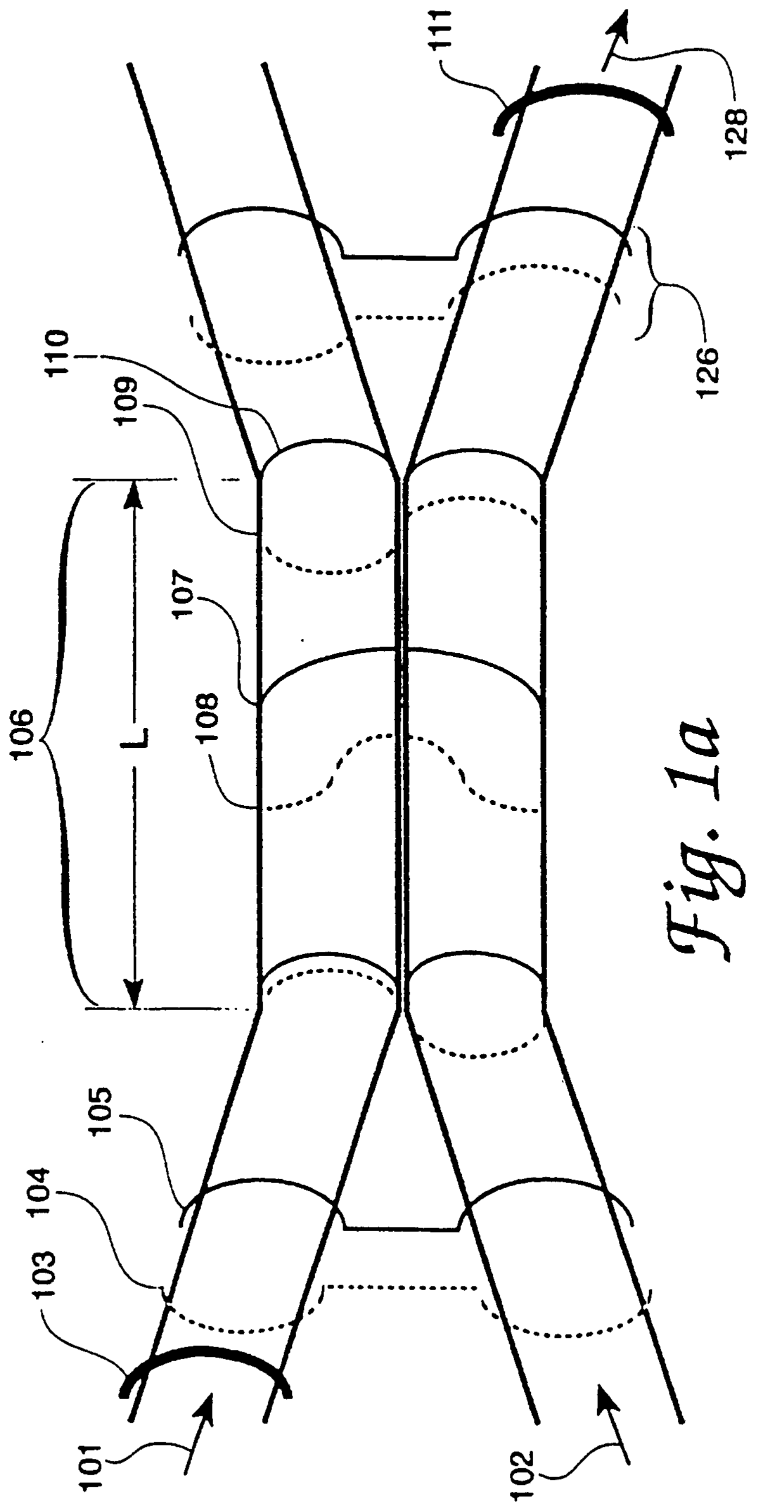


Fig. 1a
PRIOR ART

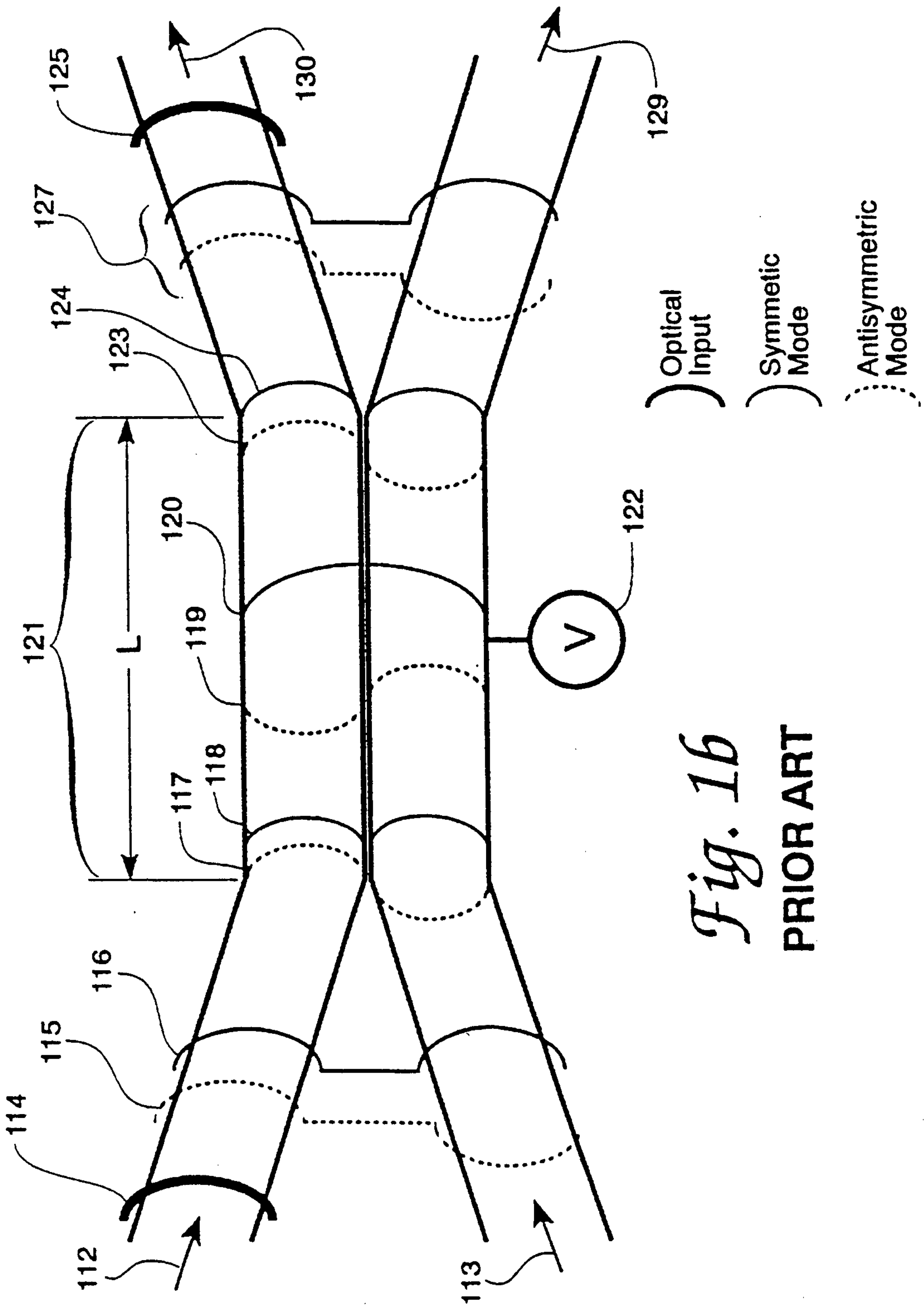


Fig. 1b
PRIOR ART

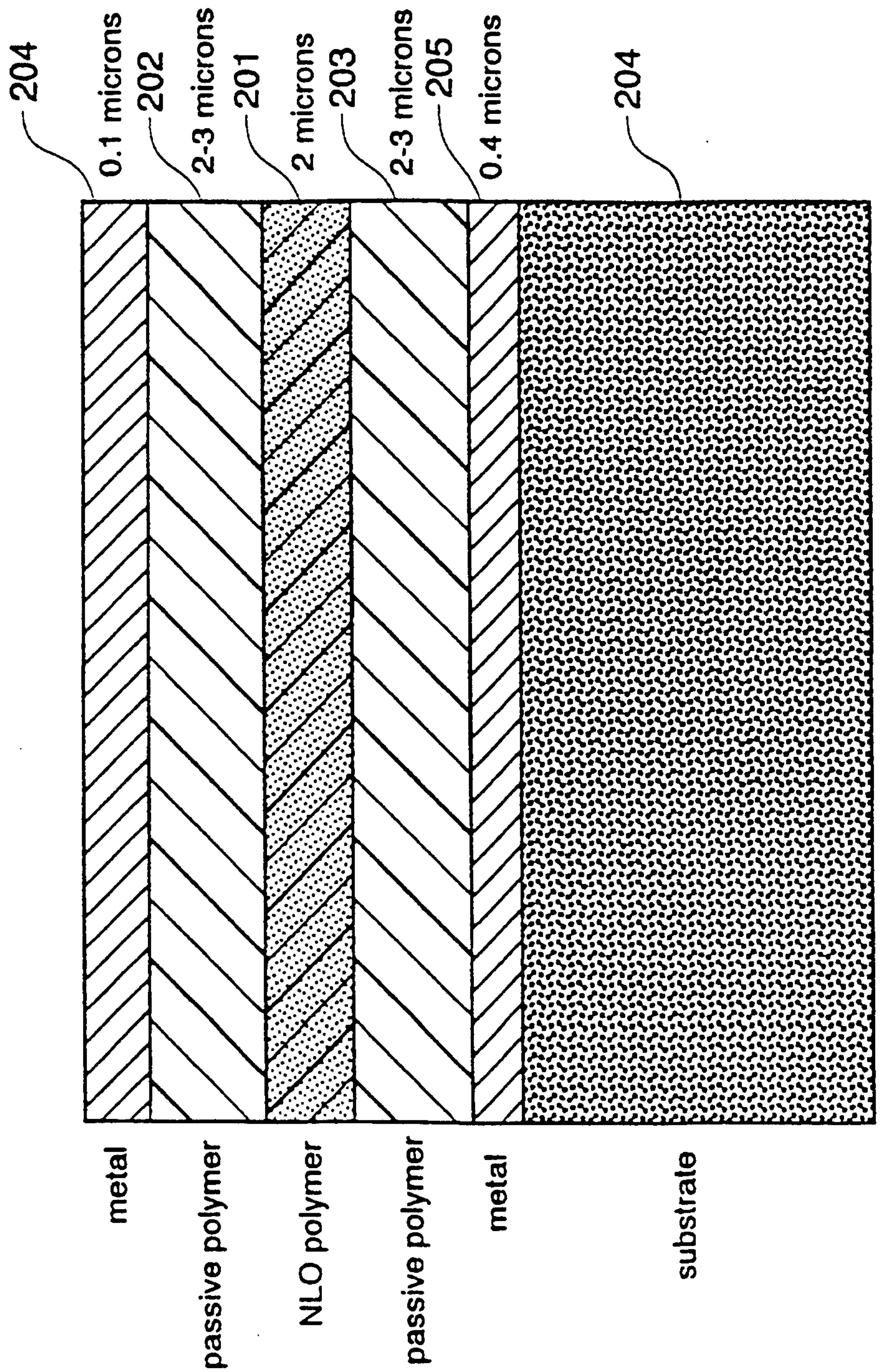


Fig. 2
Prior Art

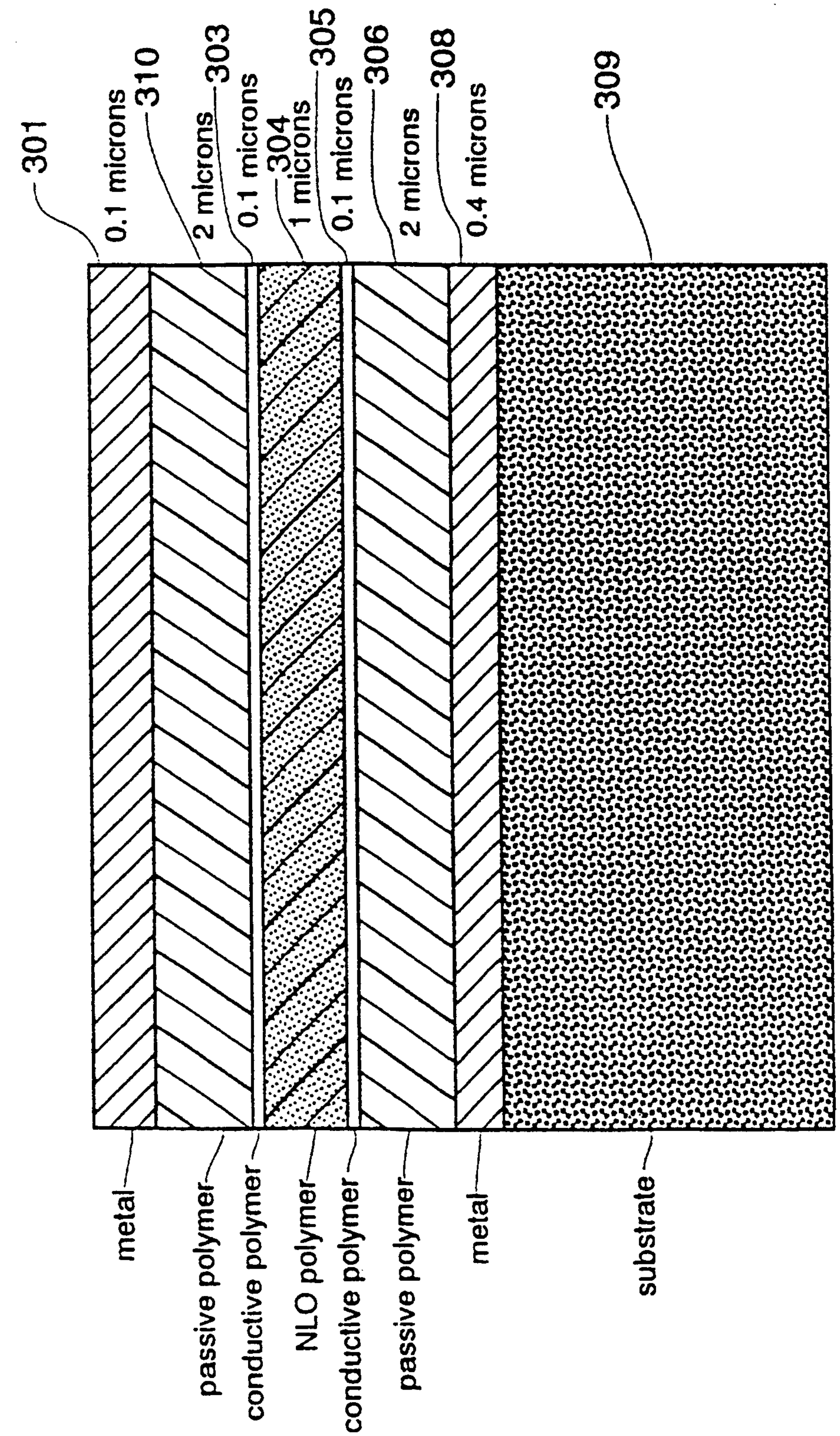

301
0.1 microns
310
2 microns
303
0.1 microns
304
1 microns
305
0.1 microns
306
2 microns
308
0.4 microns
309
metal
passive polymer
conductive polymer
NLO polymer
conductive polymer
passive polymer
metal
substrate

Fig. 3

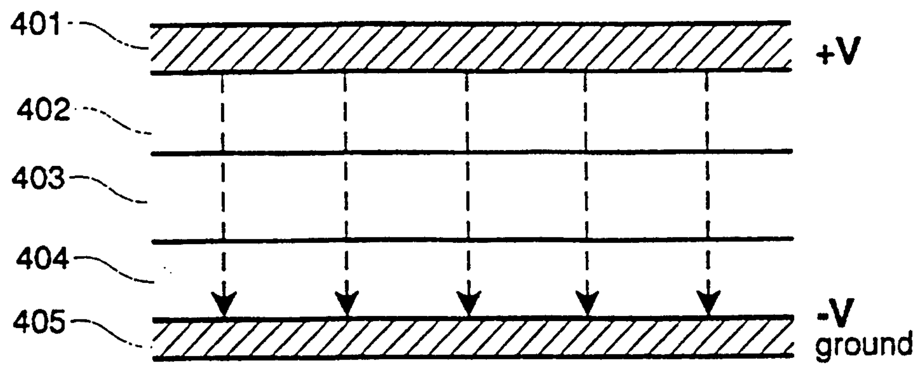


Fig. 4a

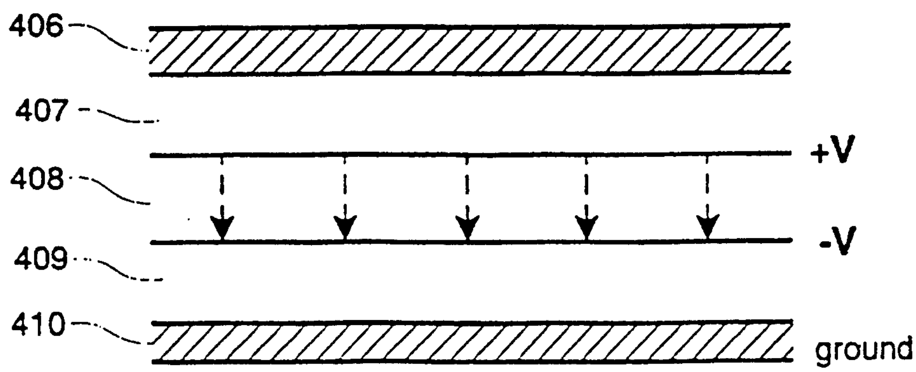


Fig. 4b

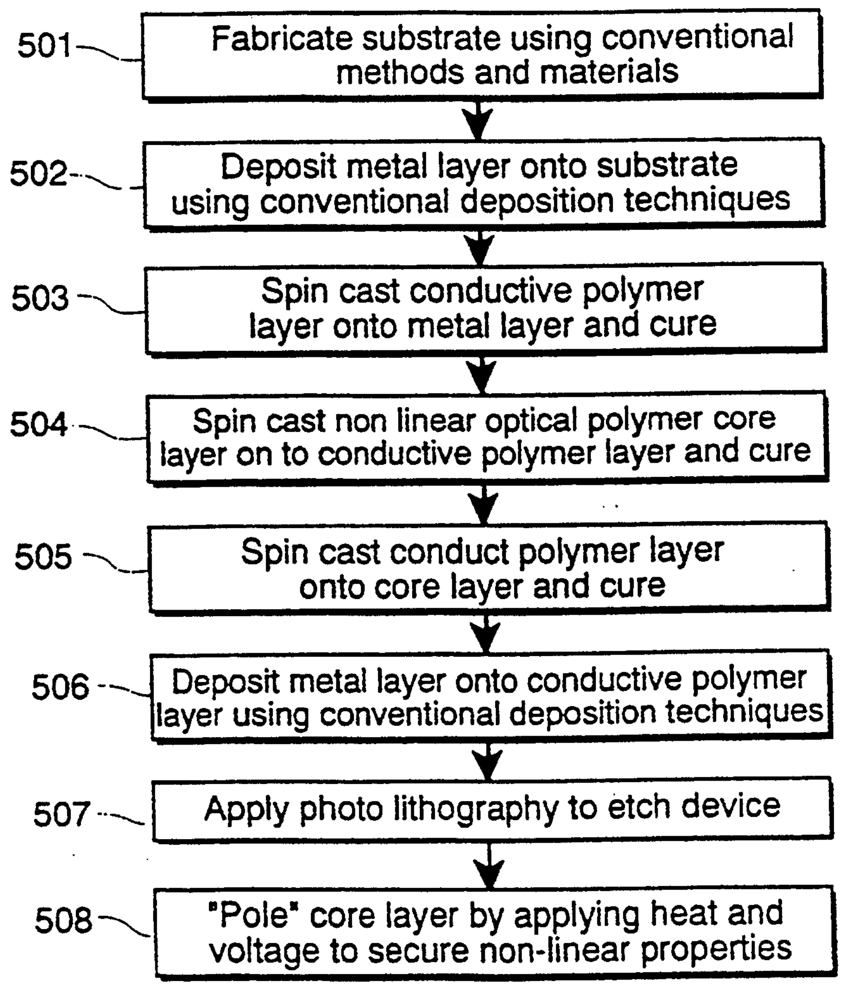

501
Fabricate substrate using conventional methods and materials
502
Deposit metal layer onto substrate using conventional deposition techniques
503
Spin cast conductive polymer layer onto metal layer and cure
504
Spin cast non linear optical polymer core layer on to conductive polymer layer and cure
505
Spin cast conduct polymer layer onto core layer and cure
506
Deposit metal layer onto conductive polymer layer using conventional deposition techniques
507
Apply photo lithography to etch device
508
"Pole" core layer by applying heat and voltage to secure non-linear properties

Fig. 5

INTEGRATED CIRCUIT COMPATIBLE ELECTRO-OPTIC DEVICE USING CONDUCTIVE POLYMER CLADDING LAYERS

RIGHTS OF THE GOVERNMENT

The invention described herein may be manufactured and used by or for the Government of the United States for all governmental purposes without the payment of any royalty.

BACKGROUND OF THE INVENTION

As optical data processing circuits approach multigigahertz operation rates, the need arises for optical signal transmission for multichip module-to-multichip module interconnection on a common board and for board-to-board interconnection through a common backplane. Currently employed electrical interconnects become impractical at multigigahertz operating rates due to electromagnetic interference and excessive power loss. As electrical interconnects are replaced with optical interconnects, there will be a need for transverse electro-optic devices for signal routing control and signal modulation. Nonlinear optical polymer transverse electro-optic devices have several attractive characteristics which many researchers have tried to capitalize on in the past decade in an effort to realize electro-optic modulators and switches for multichip module-to-multichip module and board-to-board optical interconnects. Nonlinear optical polymer includes organic based materials, inorganic based materials, and ceramic materials, as well as combinations and mixtures thereof.

A transverse electro-optic directional coupler switch is represented in the FIG. 1a top view of the device drawing of FIG. 1. As the basic form of a 2-input×2-output optical switch, the directional coupler shown in FIGS. 1a and 1b is known, with FIG. 1a showing a directional coupler without applied switching voltage and FIG. 1b showing a directional coupler with applied switching voltage. A directional coupler type of electro-optic switch is one which controls transfer of an optical signal from one channel waveguide to another by both voltage independent and voltage dependent phase changes. The applied voltage causes a change in the dielectric properties of the material and hence renders a change in the index of refraction of the material in the coupling portion which introduces a $\pi/2$ phase change through an electro-optic effect.

The FIG. 1a top view illustrates a directional coupler having ridge type waveguides etched in layers of nonlinear optical polymer material and passive polymer material.

Parallel channel waveguides, separated by a finite distance for receiving an optical signal, are represented in both FIGS. 1a and 1b at 101, 102, 112 and 113, respectively. A single optical input signal is considered for purposes of the present discussion, and this signal is represented by the bold arc at 103 and 114 in FIGS. 1a and 1b, respectively. A symmetric mode component of this optical signal, as represented at 105, and an anti-symmetric mode of the optical signal, as represented at 104 in FIG. 1a and at 116 and 115 in FIG. 1b, respectively, is generated upon the optical signal entering the directional coupler and these modes travel along the length of the channel or switch, over such lengths as are represented at 106 and 121 in FIGS. 1a and 1b, respectively. The phase of the two modes shift as the respective signals travel the length of the waveguides, as is represented in the dotted, curving lines, shown at 107 and 108 in FIG. 1a and at 119 and 120 in FIG. 1b. The symmetric mode is the mode of propagation within the waveguide region in which the optical signal is launched and the anti-symmetric mode is the mode of propagation within the other waveguide region. With no voltage applied to the FIG. 1 switches, complete transfer of light from one channel to the next occurs at a distance that introduces a voltage independent $\pi/2$ phase shift to the modes so that one mode couples completely to the other. Complete mode coupling and light transfer occurs at the output waveguides at 126 in FIG. 1a and thereafter the complete optical signal at 111 exits the waveguide at 128 in FIG. 1a.

Applying an electric field to the directional coupler of FIG. 1b over the distance L represented at 121 from the voltage source shown at 122 in FIG. 1b will alter the dielectric properties of the coupler's nonlinear material, hence changing the index of refraction of the material introducing a voltage dependent $\pi/2$ phase shift in the signal modes 115 and 116, and thereby switching the waveguide through which the optical signal exits from 129 to 130 as represented at 125 in FIG. 1b.

Past research has focused on exploiting the electro-optic properties of nonlinear optical polymers with optimized optical, structural and mechanical a properties in an attempt to achieve high-performance nonlinear optical polymer transverse electro-optic devices, such as switches and modulators. Nonlinear optical polymers have several attractive potential characteristics on which many researchers have tried to capitalize over the past decade. These include a high electro-optic coefficient enabling low voltage operation, a low dielectric constant for high-speed modulation, low temperature processing enabling integration of optics with electronics, excellent refractive index match with optical fiber materials and simplified fabrication for lower cost. A prior art conventional nonlinear optical polymer transverse electro-optic device is shown in cross-section in FIG. 2. FIG. 2 illustrates a nonlinear optical polymer core layer at 201; the optical signal is transmitted through waveguides. Passive polymer cladding layers are located at 202 and 203 in FIG. 2 and these layers operate to confine the optical signal within the core layer and limit propagation losses. Metal layers, or electrodes, initially used for poling the FIG. 2 device and during operation used for providing switching voltage are shown at 204 and 205 in FIG. 2. A voltage applied to the upper electrode 204 produces an electric field between the upper and lower electrodes, across the core polymer layer at 201 and hence changes the dielectric properties of the material, this in turn renders a change in the refractive index of the material. This is an electro-optic effect that produces a voltage dependent $\pi/2$ phase shift in the modes, causing the optical signal to switch from one waveguide to the next in the layer 201.

Several technical barriers have heretofore prevented the use of nonlinear electro-optic polymers from progressing toward commercialization much further than research devices. One of the barriers is the poling voltage requirements of such polymers. In order to align the molecules in the nonlinear optical polymer core layer 201 in FIG. 2, for example, the polymer must be "poled" once prior to the initial operation; i.e., the polymer material must be heated and subjected to a high voltage to secure the desired nonlinear optical properties of the material. The polymer material may need poling at other times during the life of the device in the event the design parameters of the device have been exceeded. For example, if the device is exposed to a temperature outside its design parameters, the nonlinear characteristics of the polymer core layer will be lost and the material will have to be poled again. A conventional nonlinear optical polymer transverse electro-optic device with

three layers of polymer material between electrodes—two cladding layers and a core layer—totaling six to eight micrometers of thickness, for example, results in a poling voltage requirement of 900 to 1200 volts (150 volts per micron of polymer thickness). Voltage levels of these magnitudes prevent easy integration of these electro-optic devices with electronics because the poling of any such electro-optic device fabricated on a single chip with other electrical devices would effectively cause high voltage damage to the other electronic and electro-optic circuit devices at the time the polymer was poled. The electro-optic device, therefore, cannot be poled insitu within an electronic integrated circuit and must be poled external to the electronic circuit. This makes monolithic integration within integrated circuits impractical. The impracticality stems from the fact that the device is fabricated and poled separately from the electronic circuit on another substrate. To interface with the electronic circuit, the conventional electro-optic device must therefore be properly aligned with the other chip components and glued in place. These steps add to the complexity of manufacturing and are much less fabrication tolerant; moreover, the poling operation may be difficult if not impossible to perform at a later time during the operating life of the device if the polymer loses its nonlinear properties.

Another barrier that has prevented nonlinear optical polymer transverse electro-optic devices from progressing much past the research stage is the required device length. Conventional switching devices are typically 14 to 27 millimeters in length. Such a length is required in a conventional nonlinear optical polymer transverse electro-optic device, for example, to enable use at a reasonable switching voltage. However, such a length also prevents integration of the device into integrated electronic circuits or electronic multichip modules.

The present invention overcomes the barriers to commercial use of nonlinear optical polymers for use in fabricating transverse electro-optic devices for electronic circuits. Using the method and device of the present invention, it is feasible to have an array of these switches in an integrated circuit chip small enough to place within a multichip module. Also, monolithic integration with electronic circuits as well as insitu poling are possible.

SUMMARY OF THE INVENTION

The present invention provides a commercially attractive arrangement for integration of transverse electro-optic devices on electronic integrated circuit chips. The invention provides for conductive polymer cladding layers immediately adjacent to an optical signal transmitting nonlinear optical polymer core layer which results in a reduced poling voltage and reduced size, allowing inclusion into integrated circuit chips of a size compatible with multichip module integration and insitu poling.

It is an object of the present invention to provide conductive polymer cladding layers adjacent to the core layer of a nonlinear optical polymer transverse electro-optic device including switches, modulators and interferometers.

It is another object of the present invention to decrease the separation between electrodes for a nonlinear optical polymer transverse electro-optic device.

It is another object of the invention to provide lower poling voltage for a nonlinear optical polymer transverse electro-optic device.

It is another object of the invention to provide a shorter length nonlinear optical polymer transverse electro-optic device.

It is another object of the invention to provide a nonlinear optical polymer transverse electro-optic device size compatible with electronic integrated circuit chip capable of multichip module integration.

It is another object of the invention to provide the capability to pole a nonlinear optical polymer transverse electro-optic device insitu within electronic circuit devices on a single integrated circuit chip.

Additional objects and features of the invention will be understood from the following description and claims and the accompanying drawings.

These and other objects of the invention are achieved by a minimal propagation loss and integrated circuit size-compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating an optical signal comprising:

- a first electrically grounded metal layer overlaying a substrate layer and functioning as an electrical ground electrode;
- a first electrically conductive polymer cladding layer overlaying said first metal layer;
- an optical signal transmitting nonlinear optical polymer core layer having electrically alterable molecular structure and optical refraction properties;
- a second electrically conductive polymer cladding layer, overlaying said optical signal transmitting nonlinear optical polymer core layer, said first and second conductive polymer layers capable of establishing an electric field region encompassing said optical signal transmitting nonlinear optical polymer core layer in said nonlinear optical polymer transverse electro-optic device; and
- a second metal layer overlaying said second conductive polymer layer and interfacing an electro-optic device controlling electrical signal voltage source with said second electrically conductive polymer layer;
- said nonlinear optical polymer core layer transmitting said optical signal in a predictably altered path therein upon application of electric field-sustaining voltage between said first and second electrically conductive polymer cladding layers.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1*a* shows a top view of a transverse electro-optic directional coupler switching device.

FIG. 1*b* shows a top view of a transverse electro-optic directional coupler switching device with an applied switching voltage.

FIG. 2 shows a cross-sectional view of a conventional nonlinear optical polymer transverse electro-optic device.

FIG. 3 shows a cross-sectional view of a nonlinear optical polymer transverse electro-optic device in accordance with the present invention.

FIG. 4*a* shows the flow of voltage applied to a conventional nonlinear optical polymer transverse electro-optic device.

FIG. 4*b* shows the flow of voltage applied to a nonlinear optical polymer transverse electro-optic device in accordance with the present invention.

FIG. 5 shows a flow diagram representing the sequence of steps for fabricating a nonlinear optical polymer transverse electro-optic device in accordance with the present invention.

DETAILED DESCRIPTION

The present invention provides reduced device length and reduced poling voltage for nonlinear optical polymer trans-

verse electro-optic devices. The invention provides conductive polymer cladding layers, in contrast to passive polymer layers, immediately adjacent to the nonlinear optical polymer core layer. The use of a conductive polymer cladding layer results in reduced separation between electrodes and hence reduced device length and reduced poling voltage for the electro-optic device, allowing inclusion of such devices into electronic integrated circuit chips of a size compatible with multichip integration. The nonlinearity of the polymer core layer is significant in such devices because it possesses the properties that allow electro-optic switching and modulation. The greater the nonlinearity, the lower the switching or modulation voltage required and the shorter the device length for a fixed separation between electrodes.

From bottom to top, the transverse electro-optic device of the present invention comprises a substrate, a metal electrode layer, a conductive polymer cladding layer, a nonlinear optical polymer core layer, a second conductive polymer cladding layer and a second metal electrode layer. The substrate may house all of the electronic circuits used in conjunction with the electro-optic device. In contrast, as described previously in FIG. 2, a conventional nonlinear electro-optic polymer transverse electro-optic device fabricated on a substrate includes a metal electrode layer, a passive polymer cladding layer, a nonlinear optical polymer core layer, a second passive polymer cladding layer and a second metal electrode layer. In the present invention, a conductive polymer cladding layer adjacent to the nonlinear optical polymer core layer produces the surprising ultimate result of greatly reducing device length while maintaining an acceptable level of propagation loss and requiring a much lower poling voltage and switching voltage than that required with conventional nonlinear optical polymer transverse electro-optic devices. The present invention is believed to be unique because using a conductive polymer material for cladding layers is not known because a conductive polymer material typically has a higher dielectric constant than a passive polymer material, and a material with a higher dielectric constant normally produces higher propagation loss. Indeed, the expected increase in propagation loss would not suggest the positive results achieved with the arrangement of the present invention.

FIG. 3 is a cross-sectional view of the layer arrangement of the present invention. The nonlinear optical polymer core layer at **301** is shown sandwiched between conductive polymer cladding layers at **302** and **303**. A layer of metal **304** is deposited on top of the optical layers in FIG. 3 and a second metal layer **305** is deposited prior to forming the optical layers on top of the substrate at **306**. The layer of metal **304** provides an interface with the electro-optic device components and electronic circuits and the metal layer at **305** functions as an electrical ground plane. The conductive polymer layers **302** and **303** operate as electrodes and are used to initially pole the nonlinear optical polymer material before operation of the device and to provide the electric field which accomplishes electro-optic switching or modulation during operation of the device. By contrast, in conventional nonlinear optical polymer transverse electro-optic devices, the layers of metal perform each of these functions. The separation distance between electrodes—i.e., the separation distance between conductive polymer layers, which equates to the thickness of the nonlinear optical polymer core layer, is significantly reduced in the arrangement of the present invention. The decrease in the separation or thickness distance between electrodes in the present invention results in benefits which make the present invention attractive for commercial electronic integrated circuit and multichip module applications where conventional devices have heretofore been lacking.

The first of these benefits is that the voltage required for poling the device prior to operation is reduced. Electric field poling is used to achieve a macroscopic alignment of chromophores within the core polymer material responsible for the electro-optic effect in nonlinear electro-optic polymers. FIG. 4*a* shows the operating distance of the poling voltage in a conventional device and FIG. 4*b* shows the operating distance of the poling voltage in an arrangement of the present invention. FIG. 4*a* shows that the poling voltage field must extend from the top electrode at **401** across the passive polymer cladding layer at **402**, through the nonlinear optical polymer core layer at **403**, across the second passive polymer cladding layer at **404** to the second metal layer at **405**, or ground. As shown in FIG. 4*a*, the electrical field must extend across the entire triple stack configuration of, approximately 6–8 microns thickness, in order to pole the nonlinear optical polymer core layer to produce the nonlinearity of the core material needed for operation of the device. With a typical poling voltage of 150 volts per micron of material, this 6–8 microns of thickness equates to a poling voltage of approximately 900–1200 volts.

By contrast, FIG. 4*b* shows that the poling voltage field for an arrangement of the present invention originates from the conductive polymer cladding layer **407** through the nonlinear optical polymer core layer at **408** to the second conductive polymer cladding layer at **409**, a distance of only 1 micron. Accordingly, the poling voltage required to pole the nonlinear optical polymer core layer using the device of the present invention is approximately 150 volts, much less than the 900–1200 volts required to pole the core layer of conventional devices.

A poling voltage of 150 volts allows the transverse electro-optic device to be fabricated as part of an electronic integrated circuit chip that can be poled insitu, within the integrated circuit chip, without harming other electronic or electro-optic devices already within the integrated circuit chip. This feature of the present invention is a major advantage over conventional devices which are not capable of monolithic inclusion into an integrated circuit chip because a 900–1200 volt poling of the polymer core material of the device prior to operation of the device cannot be practically accomplished on an integrated circuit chip containing other electronic devices. The 900–1200 volts required for poling would tend to disable the other devices. A conventional nonlinear optical polymer transverse electro-optic device would have to be poled on a separate substrate which precludes inclusion in an integrated circuit chip. The lower poling voltage which prevails for the nonlinear optical polymer transverse electro-optic device of the present invention provides significant additional advantages with respect to the electrical signal generating circuits needed to pole the device.

The voltage needed for electro-optic switching or modulation is represented mathematically by the equation

$$V=d\lambda/n^3 r_{33} L \qquad \text{Eq. 1}$$

where V is the switching or modulation voltage, d is the separation between electrodes, λ is the wavelength, n is the refractive index of the core material, r_{33} is the electro-optic coefficient of the core material and L is the length of the device. The required distance over which the switching or modulation of light occurs, i.e., the interaction length, L, is determined by the thickness and index of refraction of the core and cladding layers of the waveguides, the wavelength,

electro-optic coefficient. and applied voltage of such a device. From Eq. 1 it can be seen that. with applied voltage remaining constant. a reduced separation between electrodes. as occurs in the device of the present invention. necessarily results in a reduced interaction length. L. A conventional nonlinear optical polymer transverse electro-optic device is typically 14 to 27 millimeters in length at a wavelength of 830 nanometers. By contrast. the arrangement of the present invention employing conductive polymer cladding layers can operate at lengths as short as 2.3 millimeters at a wavelength of 830 nanometers. Such lengths can be achieved using a nonlinear optical polymer material with an electro-optic coefficient of 18 picometers/volt in the core layer **301**. A 2.3 millimeter long device can be integrated into an electronic multichip module scale circuit and combined with integrated circuit chip scale electronics while maintaining TTL switching voltage of 5 VDC.

The reduced length of the arrangement of the present invention has the added benefit of reducing the required thickness of both the nonlinear optical polymer core layer and the conductive polymer cladding layers. The shorter the device length. the shorter the distance the optical signal has to travel. so more propagation loss of the material can be tolerated relative to conventional devices. Therefore. the nonlinear optical polymer core layer and the conductive polymer cladding layers can be a lesser thickness than the same layers in conventional devices. Additionally. with a shortened device length there is inherently less optical signal propagation loss. Normally. a conductive polymer material produces greater optical signal propagation loss when operating as a cladding layer than a passive polymer material for the same distance of optical signal traveled. However in the present invention. the reduced length of the device allows the propagation loss of the device as a whole to maintain the level of propagation loss of conventional switches. i.e.. 3 decibels or less. The propagation loss may even be less than that encountered in conventional devices. depending on the nonlinear optical polymer material and conductive polymer material selected.

The arrangement of the present invention is attractive from a manufacturing standpoint because it can be fabricated using readily available equipment and techniques used in fabricating conventional electro-optic devices and electronic integrated circuits. In this regard. FIG. **5** is a flow diagram illustrating the steps for fabricating the non-linear optical polymer transverse electro-optic device arrangement of the present invention. A substrate which would house the electronics. **306** in FIG. 3. is first fabricated at block **501** in FIG. **5**. using conventionally available methods and materials known in the semiconductor art. Possible substrate materials can include semiconductor materials. metal materials. ceramic materials. polymer materials as well as combinations or mixtures thereof. Next. a thin metal layer **305** in FIG. 3. approximately 0.4 micron thick. is deposited onto the substrate using conventional metal deposition techniques as set forth in block **502** in FIG. **5**. Possible metal materials include gold. aluminum. titanium and tungsten. as well as combinations or mixtures thereof. This thin metal layer **305** win operate as a ground electrode in the arrangement of the present invention. An electrically conductive polymer cladding layer **303**. possibly hydrochloric acid doped polyaniline. polypyrole. or any other conductive polymer including organic materials. inorganic materials. ceramic materials and metal materials. as well as combinations or mixtures thereof. is spin cast onto the thin metal layer **305** and cured as set forth in block **503** in FIG. **5**.

The core layer **301**. any nonlinear optical polymer material including organic materials. inorganic materials and ceramic materials. as well as combinations or mixtures thereof. is spin cast onto the conductive polymer cladding layer **303** and subsequently cured as set forth in block **504** in FIG. **5**. A second conductive polymer layer **302** is spin cast onto the core layer and subsequently cured as set forth in block **505** in FIG. **5**. A second metal layer **304** is then deposited onto the second conductive polymer cladding layer as set forth in block **506** in FIG. **5**. After all the layers have been fabricated. the circuit is etched into the configuration of a transverse electro-optic device having the desired input and output waveguides by using photolithography as described in block **507** in FIG. **5**. Finally. the device and more specifically. the polymer core layer **301**. is poled by concurrently applying heat and a direct current voltage between metal layers **304** and **305** to secure the nonlinear properties of the core material as described in block **507** of FIG. **5**. During the poling operation. heat and DC voltage are applied to the device as per the polymer manufacturer's specifications to accomplish a satisfactory degree of poling in the nonlinear optical polymer material layer **301**.

The present invention therefore provides a commercially attractive arrangement for monolithic integration of a nonlinear optical polymer transverse electro-optic device into an electronic integrated circuit chip and insertion into a multichip module. The invention provides for conductive polymer cladding layers immediately adjacent to an optical signal transmitting nonlinear optical polymer core layer; this results in a reduced poling voltage and reduced device length. allowing nonlinear optical polymer transverse electro-optic device inclusion into electronic integrated circuit chips of a size compatible with multichip module integration. The arrangement and method of the present invention may be used to fabricate a wide variety of nonlinear optical polymer transverse electro-optic devices including directional couplers. transverse electro-optic modulators and interferometers such as Mach Zehnder interferometers.

While the apparatus and method herein described constitute a preferred embodiment of the invention. it is to be understood that the invention is not limited to this precise form of apparatus or method. and that changes may be made therein without departing from the scope of the invention which is defined in the appended claims.

What is claimed is:

1. A minimal propagation loss and integrated circuit size-compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating an optical signal comprising:

a first electrically grounded metal layer overlaying a substrate layer and functioning as an electrical ground electrode;

a first electrically conductive polymer cladding layer overlaying said first metal layer;

an optical signal transmitting nonlinear optical polymer core layer having electrically alterable molecular structure and optical refraction properties;

a second electrically conductive polymer cladding layer. overlaying said optical signal transmitting nonlinear optical polymer core layer. said first and second conductive polymer layers capable of establishing an electric field region encompassing said optical signal transmitting nonlinear optical polymer core layer in said nonlinear optical polymer transverse electro-optic device; and

a second metal layer overlaying said second conductive polymer layer and interfacing an electro-optic device

controlling electrical signal voltage source with said second electrically conductive polymer layer;

said nonlinear optical polymer core layer transmitting said optical signal in a predictably altered path therein upon application of electric field-sustaining voltage between said first and second electrically conductive polymer cladding layers.

2. The minimal propagation loss and integrated circuit size compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating an optical signal of claim 1, wherein said first and second conductive polymer cladding layers are comprised of hydrochloric acid doped polyaniline.

3. The minimal propagation loss and integrated circuit size compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating an optical signal of claim 2, wherein a thickness dimension of each of said first and second electrically conductive polymer cladding layers is less than two microns.

4. The minimal propagation loss and integrated circuit size compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating an optical signal of claim 2, wherein of said optical signal transmitting nonlinear optical polymer core layer has a thickness of one micron or less.

5. The minimal propagation loss and integrated circuit size compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating an optical signal of claim 2, wherein said total device optical signal propagation loss is less than 3 decibels.

6. The minimal propagation loss and integrated circuit size compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating an optical signal of claim 2, wherein poling voltage is between 150 and 200 volts.

7. The minimal propagation loss and integrated circuit size compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating an optical signal of claim 2, wherein said nonlinear optical polymer-based transverse electro-optic device has a length of less than 2.3 millimeters.

8. The minimal propagation loss and integrated circuit size compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating an optical signal of claim 1, wherein said first and second conductive polymer cladding layers comprise electrodes for said nonlinear optical polymer-based transverse electro-optic device operation.

9. An electrically controlled, nonlinear optical polymer-based transverse electro-optic method for switching and modulating an optical signal comprising the steps of:

transmitting an optical signal through a plurality of waveguides integral with a nonlinear optical polymer core layer;

applying an electric field to said nonlinear optical polymer core layer, said electric field commencing at a first conductive polymer cladding layer adjacent to a first lateral surface of said nonlinear optical polymer core layer and terminating at a second conductive polymer cladding layer adjacent to a second lateral surface of said nonlinear optical polymer core layer, said electric field predictably altering the phase of the optical signal in said nonlinear optical polymer core layer; and

said altering of said phase of the optical signal in said polymer core layer achieving a corresponding electro-optic altering of said optical signal within waveguides performing said optical signal steps.

10. The electrically controlled, nonlinear optical polymer-based transverse electro-optic device method for switching and modulation of an optical signal of claim 9, wherein said step of applying an electric field to said nonlinear optical polymer core layer comprises supplying a first electrical potential to a first metallic layer communicating with said first conductive polymer cladding layer and a second electrical potential to a second metallic layer communicating with said second conductive polymer layer.

* * * * *

US005892859A

United States Patent [19]

Grote

[11] **Patent Number: 5,892,859**

[45] **Date of Patent: Apr. 6, 1999**

[54] **INTEGRATED CIRCUIT COMPATIBLE ELECTRO-OPTIC CONTROLLING DEVICE FOR HIGH DATA RATE OPTICAL SIGNALS**

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[73] Assignee: **The United States of America as represented by the Secretary of the Air Force**, Washington, D.C.

[21] Appl. No.: **872,897**

[22] Filed: **Jun. 11, 1997**

[51] **Int. Cl.**[6] **G02B 6/10**

[52] **U.S. Cl.** **385/2**; 385/122; 385/8; 385/16; 385/131

[58] **Field of Search** 349/196, 197; 385/2, 122, 129, 130, 131, 8, 16, 147; 359/900

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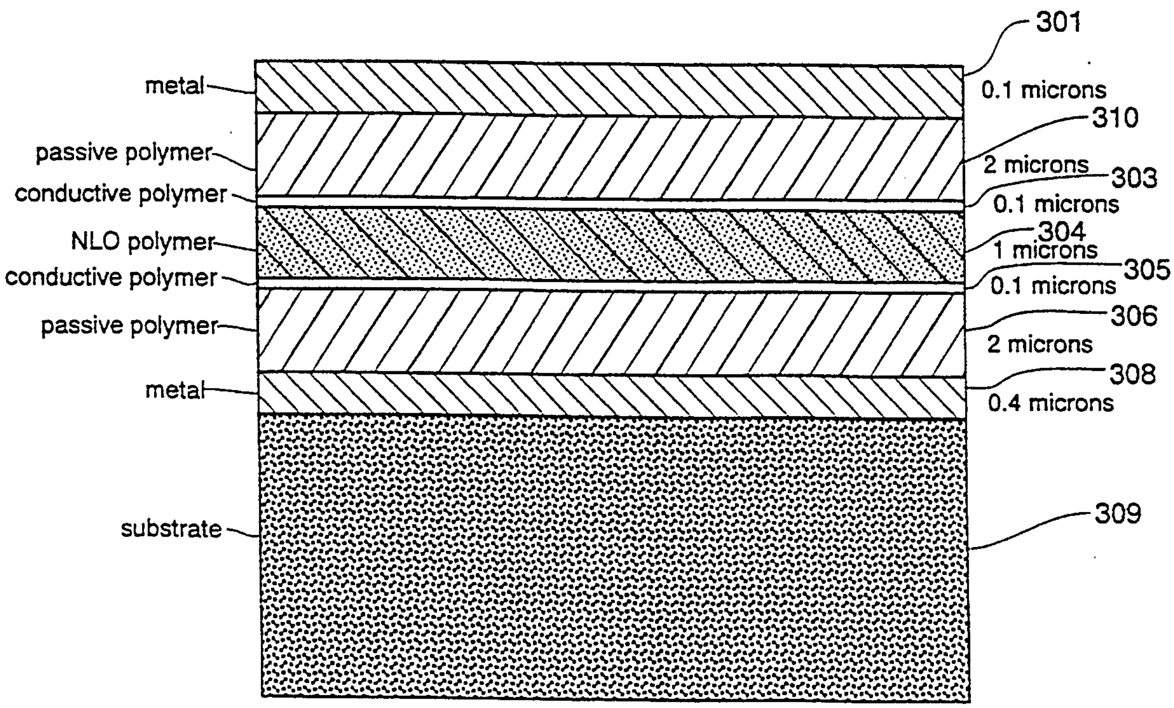
[57] **ABSTRACT**

A commercially attractive arrangement for monolithic integration of a nonlinear optical polymer transverse electro-optic device for high data rate optical signals on an electronic integrated circuit chip. The invention provides for conductive polymer sheet layers immediately adjacent to an optical signal transmitting nonlinear optical polymer core layer. Electrically passive polymer cladding layers are also provided adjacent to the conductive polymer sheet layers to achieve lower optical signal losses. The combination provides a reduced nonlinear optical polymer core layer poling voltage, reduced device length, and 5 VDC or less controlling voltage, allowing inclusion into electronic integrated circuit chips of a size compatible with multichip module integration.

19 Claims, 6 Drawing Sheets



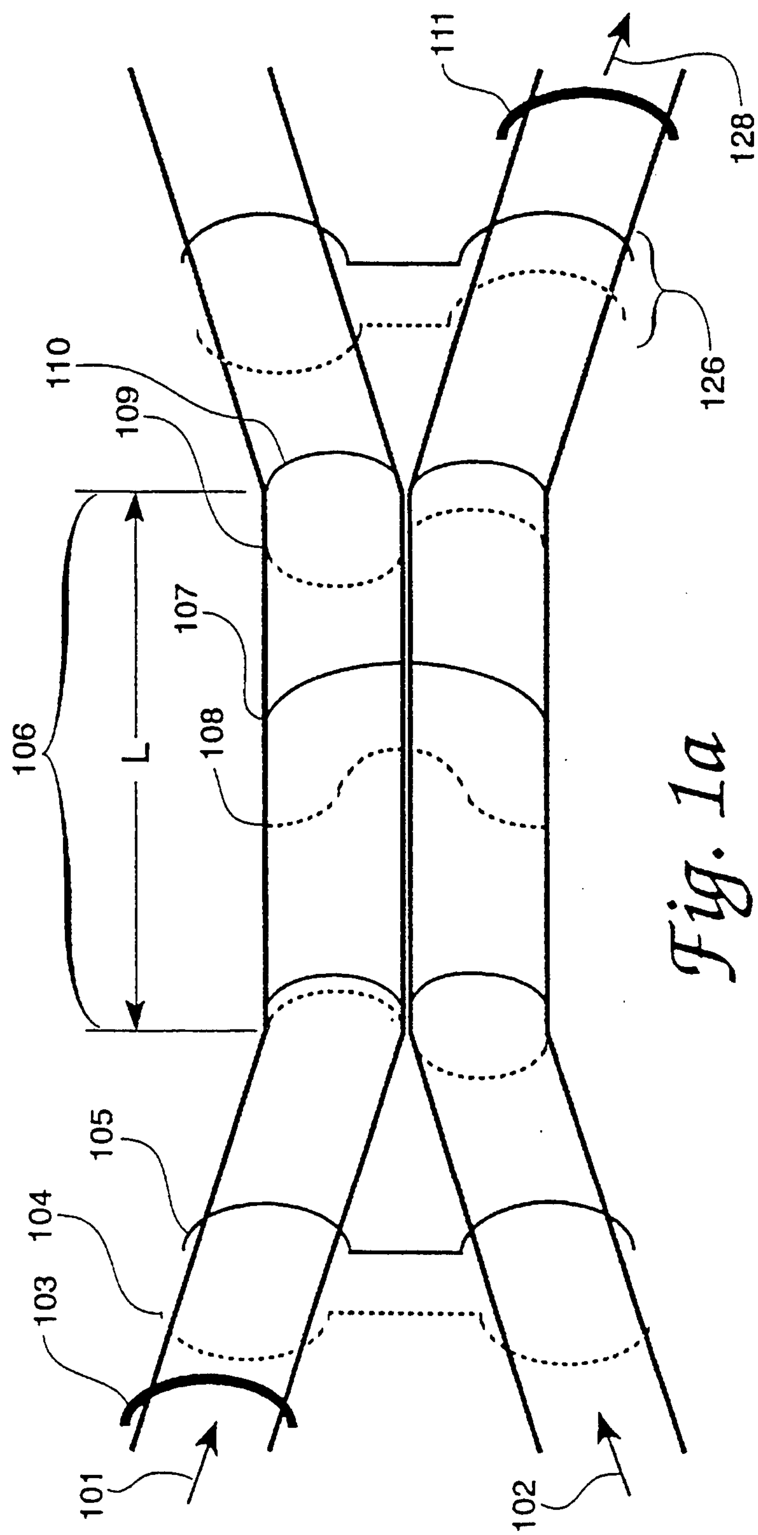


Fig. 1a
PRIOR ART

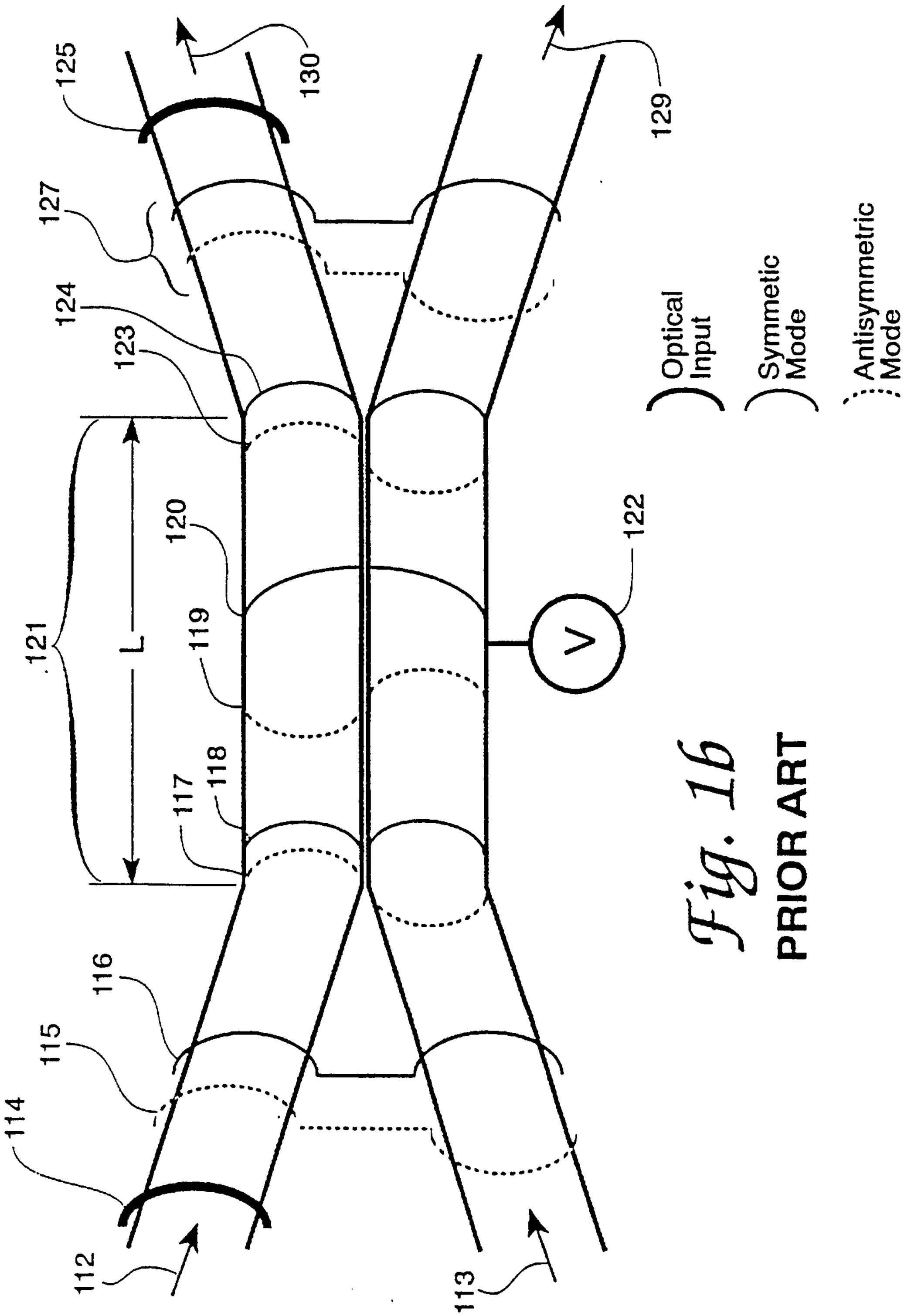


Fig. 1b
PRIOR ART

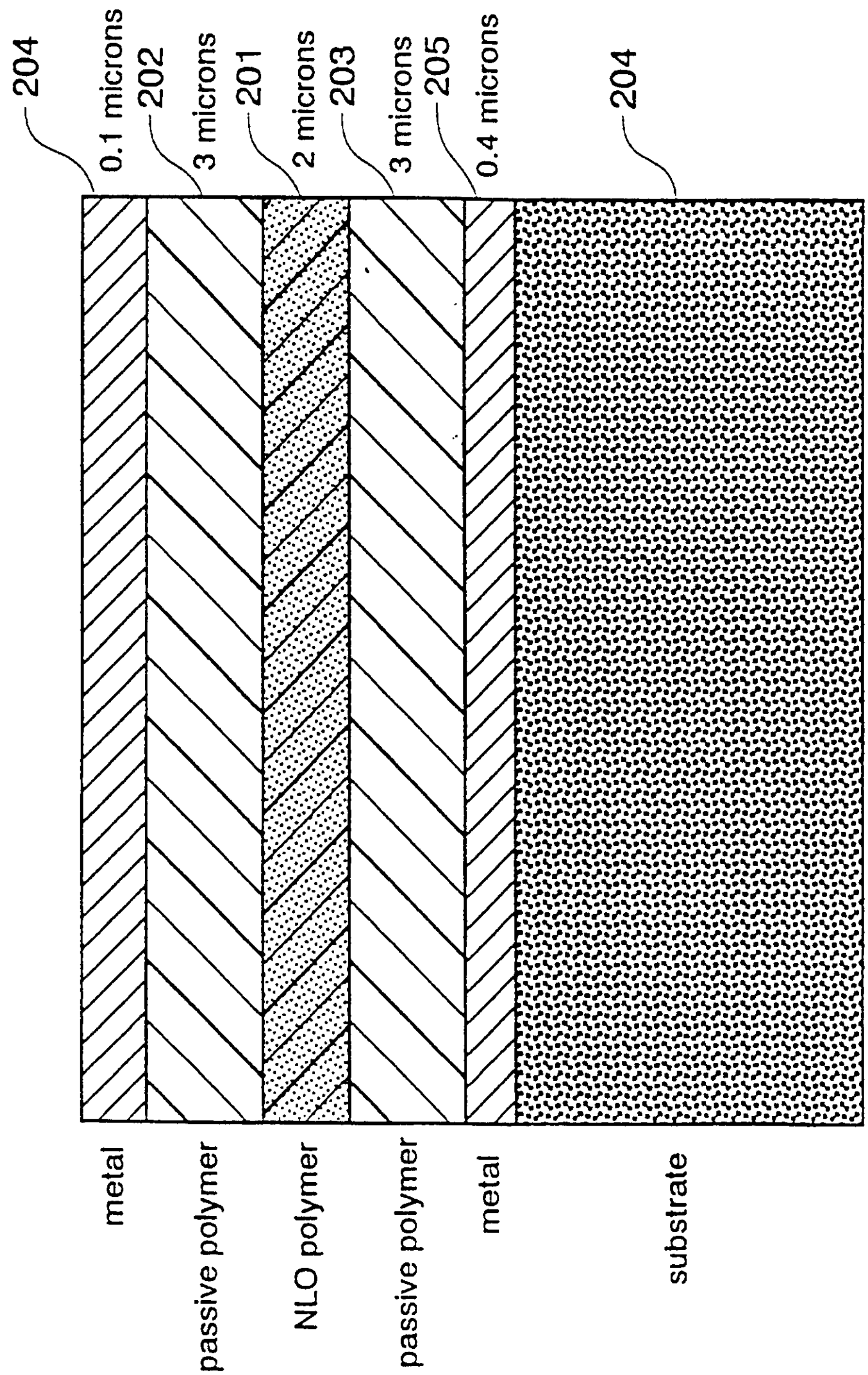


Fig. 2
Prior Art

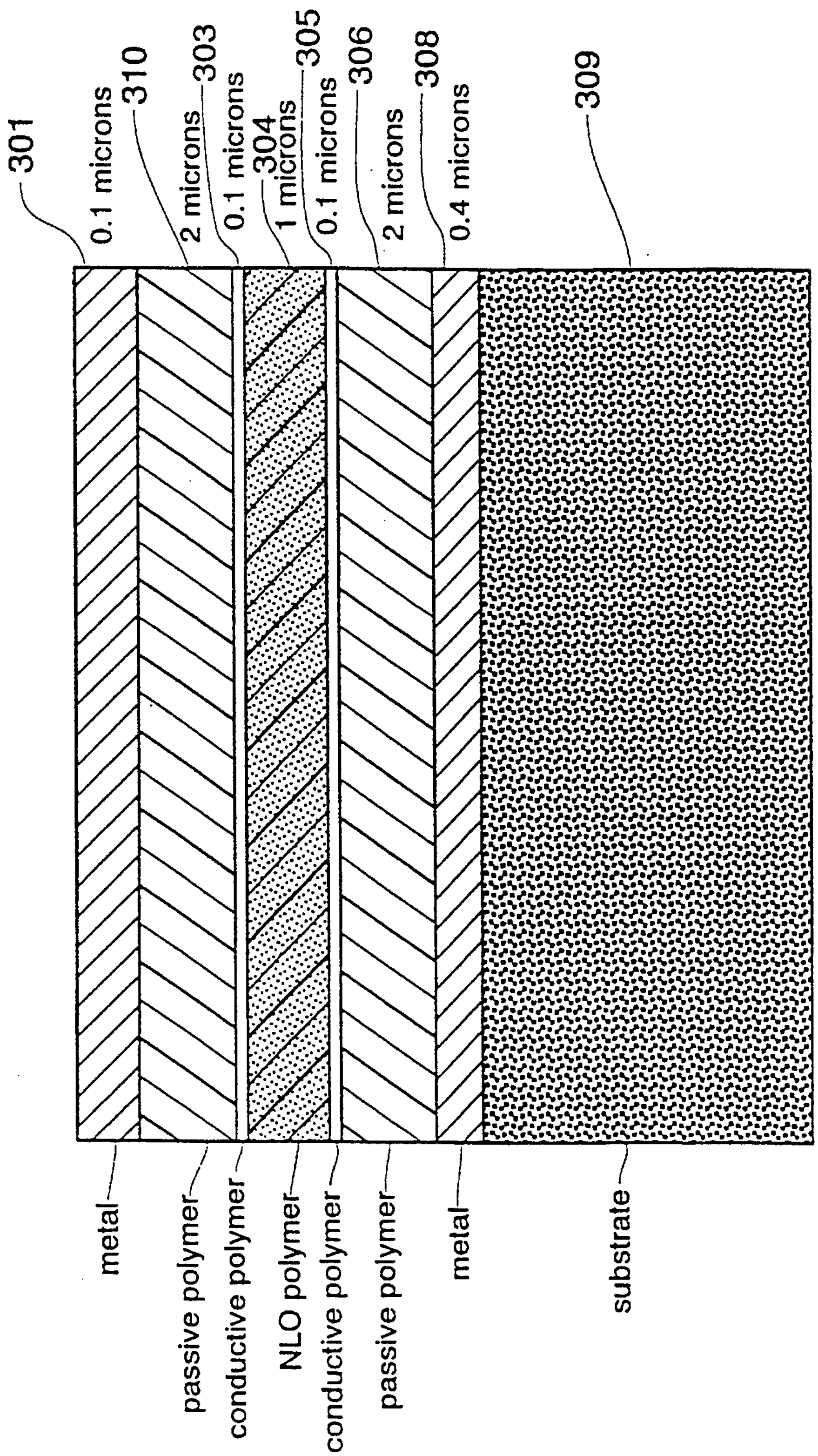

301
0.1 microns
310
2 microns
303
0.1 microns
304
1 microns
305
0.1 microns
306
2 microns
308
0.4 microns
309
metal
passive polymer
conductive polymer
NLO polymer
conductive polymer
passive polymer
metal
substrate

Fig. 3

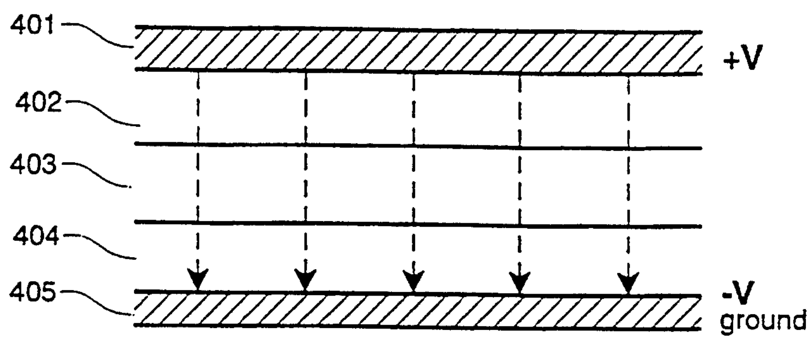

401
+V
402
403
404
405
-V
ground

Fig. 4a

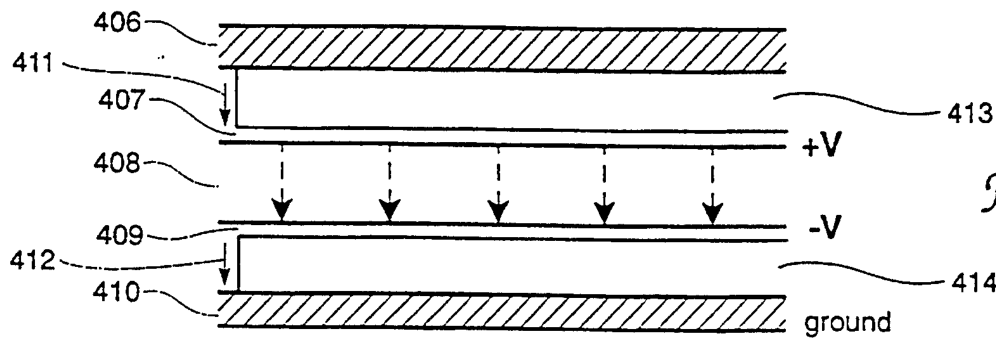

406
411
407
413
+V
408
409
-V
412
414
410
ground

Fig. 4b

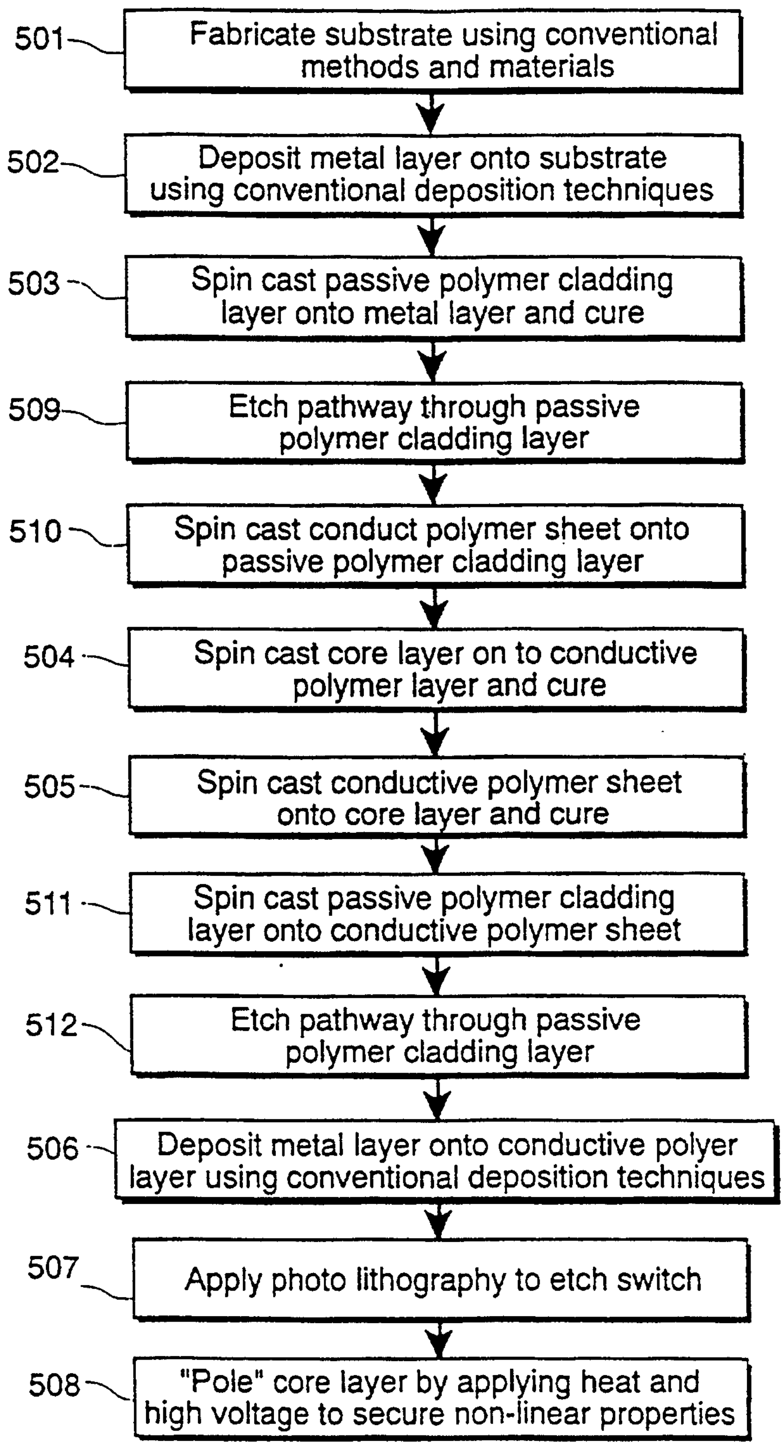

501
Fabricate substrate using conventional methods and materials
502
Deposit metal layer onto substrate using conventional deposition techniques
503
Spin cast passive polymer cladding layer onto metal layer and cure
509
Etch pathway through passive polymer cladding layer
510
Spin cast conduct polymer sheet onto passive polymer cladding layer
504
Spin cast core layer on to conductive polymer layer and cure
505
Spin cast conductive polymer sheet onto core layer and cure
511
Spin cast passive polymer cladding layer onto conductive polymer sheet
512
Etch pathway through passive polymer cladding layer
506
Deposit metal layer onto conductive polyer layer using conventional deposition techniques
507
Apply photo lithography to etch switch
508
"Pole" core layer by applying heat and high voltage to secure non-linear properties

Fig. 5

INTEGRATED CIRCUIT COMPATIBLE ELECTRO-OPTIC CONTROLLING DEVICE FOR HIGH DATA RATE OPTICAL SIGNALS

RIGHTS OF THE GOVERNMENT

The invention described herein may be manufactured and used by or for the Government of the United States for all governmental purposes without the payment of any royalty.

BACKGROUND OF THE INVENTION

This invention relates to the field of electro-optic switching and modulating devices and more particularly to electro-optic switching and modulating devices comprised of nonlinear optical polymer material.

As optical data processing circuits approach multigigahertz operation rates, the need arises for optical signal transmission for multichip module-to-multichip module interconnection on a common board and for board-to-board interconnection through a common backplane. Currently employed electrical interconnects become impractical at multigigahertz operating rates due to electromagnetic interference and excessive power loss. As electrical interconnects are replaced with optical interconnects there will be a need for transverse electro-optic devices for signal routing control and signal modulation for high data rate optical signals. For purposes of this invention, high data rate optical signals are defined as those exceeding 10 gigabits per second. Nonlinear optical polymer transverse electro-optic devices have several attractive characteristics which many researchers have tried to capitalize on in the past decade in an effort to realize electro-optic modulators and switches for multichip module-to-multichip module and board-to-board optical interconnects for high data rate optical signals. Nonlinear optical polymers have the property for which a polarization and, hence, a birefringence can be induced by an applied electric field and includes organic-based materials, inorganic-based materials and, ceramic materials, as well as combinations and mixtures thereof.

A top view of a transverse electro-optic directional coupler switch is represented in the drawing of FIG. **1**. As the basic form of a 2-input×2-output optical switch, the directional coupler, shown in FIGS. 1*a* and 1*b* is known, with FIG. 1*a* showing a directional coupler without applied switching voltage and FIG. 1*b* showing a directional coupler with applied switching voltage. A directional coupler type of electro-optic switch is one which controls transfer of an optical signal from one channel waveguide to another by both voltage independent and voltage dependent phase changes. A "transverse" electro-optic controlling device refers to an electro-optic device where the optical signal is traveling normal to the applied electric field or parallel to the electrodes. The applied voltage causes a change in the dielectric properties of the material and hence renders a change in the index of refraction of the material in the switch's coupling portion which introduces a $\pi/2$ phase change through an electro-optic effect. The FIG. 1*a* top view illustrates a directional coupler having ridge type waveguides etched in a layer of nonlinear optical polymer material and passive polymer material.

Parallel channel waveguides separated by a finite distance for receiving an optical signal are represented in both FIGS. 1*a* and 1*b* at **101**, **102** and **112** and **113**, respectively. A single optical input signal is considered for purposes of the present discussion; this signal is represented by the bold arc at **103** and **114** in FIGS. 1*a* and 1*b*, respectively. A symmetric mode component of this optical signal, as represented at **105**, and an antisymmetric mode of the optical signal as represented at **104** in FIG. 1*a* and at **116** and **115** in FIG. 1*b*, respectively, is generated upon the optical signal entering the directional coupler because of the mode coupling properties of two adjacent optical waveguides with small separation and these modes travel along the length of the channel or switch, over such lengths as are represented at **106** and **121** in FIGS. 1*a* and 1*b* respectively. The phase of the two modes shift as the respective signals travel the length of the waveguides, as is represented in the dotted, curving lines, shown at **108** in FIG. 1*a* and at **119** in FIG. 1*b* and the solid, curving lines shown at **107** and **120** in FIGS. 1*a* and 1*b* respectively. The symmetric mode is the mode of propagation within the waveguide region in which the optical signal is launched and the antisymmetric mode, the mode of propagation within the other waveguide region. With no voltage applied to the FIG. **1** switches, complete transfer of light from one channel to the next occurs at a distance that introduces a voltage independent $\pi/2$ phase shift to the modes so that one mode couples completely to the other. Complete mode coupling and light transfer occurs at the output waveguides at **126** in FIG. 1*a* and thereafter the complete optical signal at **111** exits the waveguide at **128** in FIG. 1*a*.

Applying an electric field to one of the channels of the directional coupler of FIG. 1*b* over the distance L represented at **121** from the voltage source shown at **122** in FIG. 1*b* will alter the dielectric properties of the coupler's nonlinear material subjected to the electric field, hence changing the index of refraction of the material and introducing a voltage dependent $\pi/2$ phase shift in the signal modes **115** and **116** and thereby switching the waveguide through which the optical signal exits from **129** to **130** as represented at **125** in FIG. 1*b*.

Similarly, electro-optic modulation is a rotation of the polarization of the optical signal due to an applied electric field. Maximum modulation occurs at an electric field that induces a $\pi/2$ polarization rotation.

Past research has focused on exploiting the electro-optic properties of nonlinear optical polymers with optimized optical, structural and mechanical properties in an attempt to achieve high performance nonlinear optical polymer transverse electro-optic devices, such as switches and modulators. Nonlinear optical polymers have several attractive potential characteristics on which many researchers have tried to capitalize over the past decade. These include a high electro-optic coefficient enabling low voltage operation, a low dielectric constant for high speed modulation, low temperature processing enabling integration of optics with electronics, excellent refractive index match with optical fiber materials and simplified fabrication for lower cost. A prior art conventional nonlinear optical polymer transverse electro-optic device is shown in cross-section in FIG. **2**. FIG. **2** illustrates a nonlinear optical polymer core layer at **201**; the optical signal is transmitted through waveguides. Passive polymer cladding layers are located at **202** and **203** in FIG. **2** and these layers operate to confine the optical signal within the core layer and limit propagation losses. Metal layers, or electrodes, initially used for poling the FIG. **2** device and during operation used for providing switching voltage are shown at **204** and **205** in FIG. **2**. A voltage applied to the upper electrode **204** produces an electric field between the upper and lower electrodes, across the core polymer layer at **201** and hence changes the dielectric properties of the material, which in turn renders a change in the refractive index of the material. This is an electro-optic effect that produces a voltage dependent $\pi/2$ phase shift in the layer **201** communicated signal modes, causing the optical signal to

switch from one waveguide to the next in the layer **201** of the FIG. **2** structure.

Several technical barriers have heretofore prevented the use of nonlinear electro-optic polymers from progressing toward commercialization much further than research devices. One of the barriers is the poling voltage requirements of such polymers. In order to align the molecules in the nonlinear optical polymer core layer **201** in FIG. **2**, for example, the polymer must be "poled" once prior to the initial operation; i.e., the polymer material must be heated and subjected to a high voltage to secure the desired nonlinear optical properties of the material. The polymer material may need poling at other times during the life of the device in the event the design parameters of the device have been exceeded. For example, if the device is exposed to a temperature outside the its design parameters, the nonlinear characteristics of the polymer core layer will be lost and the material will have to be poled again. A conventional nonlinear optical polymer transverse electro-optic device with three layers of polymer material between electrodes—two cladding layers and a core layer—totaling six to eight micrometers of thickness, for example, results in a poling voltage requirement of 900 to 1200 volts (150 volts per micron of polymer thickness). Voltage levels of these magnitudes prevent easy integration of these electro-optic devices with electronics because the poling of any such electro-optic device fabricated on a single chip with other electrical devices would effectively cause high voltage damage to the other electronic and electro-optic circuit devices at the time the polymer was poled. The electro-optic device, therefore, cannot be poled insitu within an electronic integrated circuit and must be poled external to the electronic circuit. This makes monolithic integration within integrated circuits impractical. The impracticality stems from the fact that the device is fabricated and poled separately from the electronic circuit on another substrate. To interface with the electronic circuit, the conventional electro-optic device must therefore be properly aligned with the other chip components and glued in place. These steps add to the complexity of manufacturing and are much less fabrication tolerant; moreover, the poling operation may be difficult if not impossible to perform at a later time during the operating life of the device if the polymer loses its nonlinear properties.

Another barrier that has prevented nonlinear optical polymer transverse electro-optic devices from progressing much past the research stage is the required device length. Conventional switching devices are typically 14 to 27 millimeters in length. Such a length is required in a conventional nonlinear optical polymer transverse electro-optic device, for example, to enable use at a reasonable switching voltage. However, such a length also prevents integration of the device into integrated electronic circuits or electronic multichip modules.

The present invention overcomes the barriers to commercial use of nonlinear electro-optic polymers for use in fabricating electro-optic devices. Using the method and device of the present invention, it is feasible to have an array of these switches in an integrated circuit chip small enough to place within a multichip module. Also, monolithic integration with electronic circuits as well as insitu poling are possible.

SUMMARY OF THE INVENTION

The present invention provides a commercially attractive arrangement for integration of high data rate transverse electro-optic devices on electronic integrated circuit chips. The invention provides for electrically conductive polymer sheet layers immediately surrounding an optical signal transmitting nonlinear optical polymer core layer in addition to passive polymer cladding layers, which results in a reduced poling voltage and reduced size, allowing inclusion into integrated circuit chips of a size compatible with multichip module integration and insitu poling.

It is an object of the present invention to provide an electro-optic switch of short length and minimal thickness capable of switching high data rate optical signals.

It is an object of the present invention to provide conductive polymer cladding sheets adjacent to the core layer of a nonlinear optical polymer transverse electro-optic device including switches, modulators and interferometers.

It is another object of the present invention to decrease the separation between electrodes for a nonlinear optical polymer transverse electro-optic device.

It is another object of the invention to provide lower poling voltage for a nonlinear optical polymer transverse electro-optic device.

It is another object of the invention to provide a shorter length nonlinear optical polymer transverse electro-optic device.

It is another object of the invention to provide a nonlinear optical polymer transverse electro-optic device size compatible with an electronic integrated circuit chip capable of multichip module integration.

It is another object of the invention to provide the capability to pole a nonlinear optical polymer transverse electro-optic device insitu within electronic circuit devices on a single integrated circuit chip.

Additional objects and features of the invention will be understood from the following description and claims and the accompanying drawings.

These and other objects of the invention are achieved by a minimal propagation loss and integrated circuit size-compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating a high data rate optical signal comprising:

- a first electrically grounded metal layer overlaying a substrate layer and functioning as an electrical ground electrode;
- a first electrically passive polymer cladding layer overlaying said first metal layer and including therein an aperture communicating with said grounded metal layer;
- a first electrically conductive polymer sheet layer overlaying said first electrically passive polymer layer, said electrically conductive polymer sheet layer including an integral portion extending through said aperture of said first electrically passive polymer layer and making electrical contact with said first electrically grounded metal layer;
- an optical signal transmitting nonlinear optical polymer core layer having electrically alterable molecular structure and optical refraction properties;
- said nonlinear optical polymer core layer being capable of transmitting said optical signal in a predictably altered path therein upon application of a transverse electric field thereto;
- a second electrically conductive polymer sheet layer overlaying said optical signal transmitting nonlinear optical polymer core layer, said first and second conductive polymer sheet layers being capable of estab-

lishing an electric field region encompassing said optical signal transmitting nonlinear optical polymer core layer in said electro-optic device;

a second electrically passive polymer cladding layer overlaying said second electrically conductive polymer sheet layer including an electrical conductor-receiving aperture therethrough;

a second metal layer overlaying said second electrically passive polymer cladding layer and interfacing an electro-optic device controlling electrical signal voltage source with extension of said second electrically conductive polymer sheet; and

an electrical conductor member extending from said second electrically conductive polymer sheet layer through said conductor receiving aperture of said second electrically passive polymer cladding layer to said second metal layer.

DESCRIPTION OF THE DRAWINGS

FIG. 1*a* shows a top view of a transverse electro-optic directional coupler switching device.

FIG. 1*b* shows a top view of a transverse electro-optic directional coupler switching device with an applied switching voltage.

FIG. 2 shows a cross-sectional view of a conventional nonlinear optical polymer transverse electro-optic device.

FIG. 3 shows a cross-sectional view of a nonlinear optical polymer transverse electro-optic device in accordance with the present invention.

FIG. 4*a* shows the electric field applied to a conventional nonlinear optical polymer transverse electro-optic device.

FIG. 4*b* shows the electric field applied to a nonlinear optical polymer transverse electro-optic device in accordance with the present invention.

FIG. 5 shows a flow diagram representing the sequence of steps for fabricating a nonlinear optical polymer transverse electro-optic device in accordance with the present invention.

DETAILED DESCRIPTION

The present invention provides reduced device length and reduced poling voltage for nonlinear optical polymer transverse electro-optic devices for high data rate optical signals. The invention provides electrically conductive polymer sheet layers immediately adjacent to the nonlinear optical polymer core layer of such an electro-optic device in addition to passive polymer cladding layers. The use of electrically conductive polymer sheet layers results in reduced separation between electrodes and hence reduced device length and reduced poling voltage for the electro-optic device, allowing inclusion of such devices into integrated circuit chips of a size compatible with multichip integration. The nonlinearity of the polymer core layer is significant in such devices because it possess the properties that allow electro-optic switching and modulation. The greater the nonlinearity, the lower the switching or modulation voltage required and the shorter the device length for a fixed separation between electrodes. Also, the combination of electrically conductive polymer sheet layers and passive polymer cladding layers provides switching or modulation of high data rate signal propagation paths with minimal propagation loss.

From bottom to top, the transverse electro-optic device of the present invention comprises a substrate, a metal electrode layer, a passive polymer cladding layer, a conductive polymer sheet layer, a nonlinear optical polymer core layer, a second conductive polymer sheet layer, a second passive polymer cladding layer and a second metal electrode layer. The substrate may house all of the electronic circuits used in conjunction with the electro-optic device. In contrast, as described previously in FIG. 2, a conventional nonlinear polymer transverse electro-optic device fabricated on a substrate includes a metal electrode layer, a passive polymer cladding layer, a nonlinear optical polymer core layer, a second passive polymer cladding layer and a second metal electrode layer. In the present invention, a thin, electrically conductive polymer layer, or sheet, adjacent the nonlinear optical polymer core layer produces the surprising ultimate result of reducing device length, minimizing propagation loss and requiring much lower poling voltage and switching voltage than that required with conventional nonlinear optical polymer transverse electro-optic devices.

FIG. 3 is a cross-sectional view of the layer arrangement of the present invention. The nonlinear optical polymer core layer at **304** having a thickness of one micron, is shown sandwiched between the conductive polymer sheet layers at **303** and **305**, each conductive polymer sheet having a thickness of 0.1 micron. Adjacent each conductive polymer sheet layer, on a side opposite the nonlinear optical polymer core layer **304**, is an electrically passive polymer cladding layer, shown at **310** and **306**, each having a thickness of two microns. The passive polymer cladding layer **310** contains an aperture or pathway, shown at **302**, which contains a deposit of metal material, an extension of metal layer **301**. Similarly, the passive polymer cladding layer **306** contains an aperture or pathway, shown at **307**, which contains a deposit of electrically conductive polymer material, an extension of the electrically conductive polymer sheet layer **305**. A layer of metal **301** is deposited on top of the optical layers in FIG. 3 and a second metal layer **308** is deposited prior to forming the optical layers on top of the substrate at **309**.

The FIG. 3 layer of metal **301** provides a physical interface with other electro-optic device components and electronic circuits and the metal layer at **308** functions as an electrical ground plane. A voltage source, not shown, is connected between metal layers **301** and **308** and the voltage establishes an electric field region therebetween, through the passive polymer cladding layer at aperture **302**, which contains a metal material, to the electrically conductive polymer sheet layer at **303**. An electrical field is then created across the nonlinear optical polymer core layer **304** between conductive polymer cladding sheets **303** and **305**. The electric field generated by the voltage source encompasses conductive polymer sheet layer **305** through the extension of such sheet layer at **307** within the aperture or pathway of passive polymer layer **306** and terminates at the electrical ground metal layer **308**. For manufacturing convenience, the apertures within the passive polymer cladding layers contain in one instance metal from the top metal layer, and in the second instance conductive polymer, although both materials are electrically conductive and function to minimize the distance the voltage generated electric field extends. Therefore, electrically conductive polymer sheet layers **303** and **305** operate as electrodes and are used to initially pole the nonlinear optical polymer material before operation of the device and to provide the electric field which accomplishes optical switching during operation of the device. By contrast, in conventional nonlinear optical polymer transverse electro-optic devices, the layers of metal perform each of these functions. The separation distance between effective

electrode layers—i.e., the separation distance between conductive polymer sheet layers—which equates to the thickness of the nonlinear optical polymer core layer—is significantly reduced in the arrangement of the present invention. The decrease in the separation or thickness distance between effective electrode layers in the present invention results in benefits which make the present invention attractive for commercial electronic integrated circuit and multichip module applications where conventional devices have heretofore been lacking.

The first of these benefits is that the voltage required for poling the device prior to operation is reduced. Electric field poling is used to achieve a macroscopic alignment of chromophores within the core polymer material responsible for the electro-optic effect in nonlinear electro-optic polymers. FIG. 4*a* shows the operating distance of the poling voltage in a conventional device and FIG. 4*b* shows the operating distance of the poling voltage in an arrangement of the present invention. FIG. 4*a* shows that the poling voltage field must extend from the top electrode at **401** across the passive polymer cladding layer at **402**, through the nonlinear optical polymer core layer at **403**, across the second passive polymer cladding layer at **404** until the second metal layer at **405**, or ground. As shown in FIG. 4*a*, the electrical field must extend across the entire triple stack configuration of approximately 6–8 microns thickness, in order to pole the nonlinear optical polymer core layer to produce the nonlinearity of the core material needed for operation of the device. With a typical poling voltage of 150 volts per micron of material, this 6–8 microns of thickness equates to a poling voltage approximately 900–1200 volts.

By contrast, FIG. 4*b* shows that the poling voltage field for an arrangement of the present invention to originate at top metal layer **406**, conduct along the metal pathway **411** through the passive polymer cladding layer **413**. The voltage field then operates from the conductive polymer sheet layer **407** through the nonlinear optical polymer core layer at **408** to the second conductive polymer sheet layer at **409**, a distance of only 1 micron. Accordingly, the poling voltage required to pole the nonlinear optical polymer core layer using the device of the present invention is approximately 150 volts, much less than the 900–1200 volts required to pole the core layer of conventional devices. The electric field lines extend along the pathway of conductive polymer material **412** located in the passive polymer cladding layer **414** and terminates at electrical ground **410**.

It should be appreciated that even though the electrical aspects of the FIG. 4*b* arrangement of the present invention pass over or ignore the presence of the electrically passive polymer layers **413** and **414** in FIG. 4*b* , these layers are nevertheless significant with respect to optical properties of the FIG. 4*b* device. These layers in fact serve to reduce optical signal propagation losses incurred in the FIG. 4*b* device. The optical signal propagation loss prevention is in small part achieved by the electrically conductive polymer layers **407** and **409**, however, these layers are so thin as to need supplementation by the layers **413** and **414**.

A poling voltage of 150 volts allows the transverse electro-optic device to be fabricated as part of an electronic integrated circuit chip that can be poled insitu, within the integrated circuit chip, without harming other electronic or electro-optic devices. This feature of the present invention is a major advantage over conventional devices which are not capable of monolithic inclusion into an integrated circuit chip because a 900–1200 volt poling of the polymer core material of the device prior to operation of the device cannot be practically accomplished on an integrated circuit chip containing other electronic devices. The 900–1200 volts required for poling would tend to disable the other devices. A conventional nonlinear optical polymer transverse electro-optic device would have to be poled on a separate substrate which precludes inclusion in an integrated circuit chip. The lower poling voltage which prevails for the nonlinear optical polymer transverse electro-optic device of the present invention provides significant additional advantages with respect to the electrical signal generating circuits needed to operate the device.

The voltage needed for electro-optic control is represented mathematically by the equation

$$V = d\lambda / n^3 r_{33} L \qquad \text{Eq. 1}$$

where V is the switching or modulation voltage, d is the separation between electrodes, λ is the wavelength, n is the refractive index of the core material, r_{33} is the electro-optic coefficient of the core material and L is the length of the device. The required distance over which the switching or modulation of light occurs, i.e. the interaction length L, is determined by the thickness and index of refraction of the core and cladding layers of the waveguides, the wavelength, electro-optic coefficient and applied voltage of such a device. From Eq. 1 it can be seen that, with applied voltage remaining constant or reduced, a reduced separation between electrodes, as occurs in the device of the present invention, necessarily results in a reduced interaction length, L. A conventional nonlinear optical polymer transverse electro-optic device is typically 14 to 27 millimeters in length at a wavelength of 830 nanometers. By contrast, the arrangement of the present invention employing both conductive polymer sheet layers and passive polymer cladding layers can operate at lengths as short as 2.3 millimeters at a wavelength of 830 nanometers. Such lengths can be achieved using a nonlinear optical polymer material with an electro-optic coefficient of 18 picometers/volt in the core layer **301**. A 2.3 millimeter long device can be integrated into an electronic multichip module scale circuit and combined with integrated circuit chip scale electronics while maintaining TTL switching voltage of 5VDC.

The reduced length of the arrangement of the present invention has the added benefit of reducing the required thickness of both the nonlinear optical polymer core layer and the passive polymer cladding layers. The shorter the device length, the shorter the distance the optical signal has to travel, so more propagation loss of the material can be tolerated relative to conventional devices. Therefore, both the nonlinear optical polymer core layer and the passive polymer cladding layers can be a lesser thickness than the same layers in conventional devices.

Additionally, with a shortened device length, there is inherently less optical signal propagation loss. The degree of propagation loss is significant in the arrangement of the present invention because the use of electrically conductive polymer sheet layers surrounding a polymer layer transmitting high data rate optical signals would generally generate noise and erroneous optical signals. Further, the conductive polymer sheet layers, in the presence of high data rate optical signals, would begin to operate in the manner of an antenna and interfere with operation of electronic devices in close proximity. Conventional electro-optic switching devices employ passive polymer cladding layers to confine, or reduce propagation loss of the optical signal in the nonlinear optical polymer core layer. In contrast, a conductive polymer material, as is used in the sheet layers of the present invention, produces greater optical signal propagation loss when surrounding an optical signal transmitting

layer for the same distance of optical signal traveled. However in the present invention. the reduced length of the switch along with the signal confining passive polymer cladding layers surrounding the conductive polymer sheet layers allows the propagation loss of the switch to. in fact. be less than the 3 decibels of conventional devices.

The arrangement of the present invention is attractive from a manufacturing standpoint because it can be fabricated using readily available equipment and techniques used in fabricating conventional electro-optic devices and electronic integrated circuits. In this regard. FIG. 5 is a flow diagram illustrating the steps for fabricating the nonlinear optical polymer transverse electro-optic device arrangement of the present invention. A substrate. **309** in FIG. 3. is first fabricated at block **501** in FIG. 5. using conventionally available methods and materials known in the semiconductor art. Possible substrate materials include semiconductor materials. metal materials. ceramic materials and polymer materials as well as combinations or mixtures thereof. Next a thin metal layer. **308** in FIG. 3. approximately 0.4 micron thick is deposited onto the substrate using conventional metal deposition techniques as set forth in block **502** in FIG. 5. Possible metal layer materials include gold. aluminum. titanium and tungsten as well as combinations or mixtures thereof. This thin metal layer **308** will operate as a ground electrode in the arrangement of the present invention.

An electrically passive polymer cladding layer **306** is spin cast onto the thin metal layer **308** and cured as set forth in block **503** in FIG. 5. An aperture or pathway. **302** or **307**. is then etched into the passive polymer cladding layer **306** using photolithography. such pathway fabrication being set forth at **509** in FIG. 5. An electrically conductive polymer material is then spin cast onto the passive polymer cladding layer in a sheet. in a thin thickness of less than 0.1 micron. filling the aperture **307** within the passive polymer cladding layer **306** as set forth in block **510** of FIG. 5. Possible electrically conductive polymer materials include hydrochloric acid doped polyaniline. polypyrole. or any other conductive polymer including organic materials. inorganic materials. ceramic materials and metal materials as well as combinations or mixtures thereof.

The core layer **304**. any nonlinear optical polymer material including organic materials. inorganic materials and ceramic materials as well as combinations or mixtures thereof. is spin cast onto the conductive polymer sheet layer **305** and subsequently cured as set forth in block **504** in FIG. 5. A second conductive polymer sheet layer **303** of less than 0.1 micron thickness is spin cast onto the nonlinear optical polymer core layer and subsequently cured as set forth in block **505** in FIG. 5. A second passive polymer layer **310** is then deposited onto the second conductive polymer sheet as set forth in block **511** in FIG. 5.

An aperture or pathway **302** is then etched into the second passive polymer layer **310** as set forth in block **512** of FIG. 5. After etching. a layer of metal **301** is deposited onto the passive polymer layer **310**. filling in the pathway **302** so it is thereby conductive. After all the layers have been fabricated. the circuit is etched into the configuration of a transverse electro-optic device having the desired input and output waveguides by using photolithography as described in block **507** in FIG. 5. Finally the switch. and more specifically the polymer core layer **301**. is poled by concurrently applying heat and a direct current voltage between metal layers **304** and **305** to secure the nonlinear properties of the core material as described in block **507** of FIG. 5. During the poling operation heat and DC voltage are applied to the device as per the polymer manufacturer's specifications to accomplish a satisfactory degree of poling in the nonlinear optical polymer material layer **304**.

The present invention therefore provides a commercially attractive arrangement for monolithic integration of an high data rate nonlinear optical polymer transverse electro-optic device into an electronic integrated circuit chip and insertion into a multichip module. The invention provides for conductive polymer sheet layers immediately adjacent an optical signal transmitting nonlinear optical polymer core layer; this results in a reduced poling voltage and reduced length. allowing nonlinear optical polymer transverse electro-optic device inclusion into electronic integrated circuit chips of a size compatible with multichip module integration. The arrangement and method of the present invention may be used to fabricate a wide variety of nonlinear optical polymer transverse electro-optic devices including directional couplers. transverse electro-optic modulators and interferometers such as Mach Zehnder interferometers.

While the apparatus and method herein described constitute a preferred embodiment of the invention. it is to be understood that the invention is not limited to this precise form of apparatus or method and that changes may be made therein without departing from the scope of the invention which is defined in the appended claims.

What is claimed is:

1. A minimal propagation loss and integrated circuit size-compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating a high data rate optical signal comprising:

a first electrically grounded metal layer overlaying a substrate layer and functioning as an electrical ground electrode;

a first electrically passive polymer layer cladding overlaying said first metal layer and including therein an aperture communicating with said grounded metal layer;

a first electrically conductive polymer sheet layer overlaying said first electrically passive polymer layer. said electrically conductive polymer sheet layer including an integral portion extending through said aperture of said first electrically passive polymer layer and making electrical contact with said first electrically grounded metal layer;

an optical signal transmitting nonlinear optical polymer core layer having electrically alterable molecular structure and optical refraction properties;

said nonlinear optical polymer core layer being capable of transmitting said optical signal in a predictably altered path therein upon application of a transverse electric field thereto;

a second electrically conductive polymer sheet layer overlaying said optical signal transmitting nonlinear optical polymer core layer. said first and second conductive polymer sheets being capable of establishing an electric field region encompassing said optical signal transmitting nonlinear optical polymer core layer in said electro-optic device;

a second electrically passive polymer cladding layer overlaying said second electrically conductive polymer sheet including an electrical conductor-receiving aperture therethrough;

a second metal layer overlaying said second electrically passive polymer cladding layer and interfacing an electro-optic device controlling electrical signal voltage source with extension of said second electrically conductive polymer sheet: and

an electrical conductor member extending from said second electrically conductive polymer sheet layer through said conductor receiving aperture of said second electrically passive polymer cladding layer to said second metal layer.

2. The minimal propagation loss and integrated circuit size-compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device of claim 1 wherein said electrical conductor member is comprised of second electrically conductive polymer sheet layer material.

3. The minimal propagation loss and integrated circuit size compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating high data rate optical signals of claim 1, wherein said first and second conductive polymer sheets are comprised of hydrochloric acid doped polyaniline.

4. The minimal propagation loss and integrated circuit size compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating high data rate optical signals of claim 3, wherein a thickness dimension of each of said first and second electrically conductive polymer sheet is 0.1 micron.

5. The minimal propagation loss and integrated circuit size-compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating high data rate optical signals of claim 3, wherein said optical signal transmitting nonlinear optical polymer core layer has a thickness of one micron or less.

6. The minimal propagation loss and integrated circuit size-compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating high data rate optical signals of claim 3, wherein said electrically passive polymer cladding layers each have a thickness of 2 microns.

7. The minimal propagation loss and integrated circuit size-compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating high data rate optical signals of claim 3, wherein said high data rate optical signals have a propagation loss less than 3 decibels.

8. The minimal propagation loss and integrated circuit size-compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating high data rate optical signals of claim 3, wherein said nonlinear optical polymer core layer has a thickness responsive to a poling voltage between 150 and 200 volts.

9. The minimal propagation loss and integrated circuit size-compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating high data rate optical signals of claim 3, wherein said electro-optic device has a length of less than 2.3 millimeter.

10. The minimal propagation loss and integrated circuit size-compatible electrically controlled nonlinear optical polymer-based transverse electro-optic device for switching and modulating high data rate optical signals of claim 1, wherein said first and second electrically conductive polymer sheets comprise a dielectric property-controlling electrical signal input port of said optical signal transmitting nonlinear optical polymer core layer.

11. A method for fabricating a high data rate nonlinear optical polymer transverse electro-optic device comprising the steps of:

depositing a first metal layer onto a substrate;

forming a first electrically passive polymer cladding layer onto said metal layer;

etching an aperture into said first electrically passive polymer layer;

forming a first electrically conductive polymer sheet onto said first electrically passive polymer cladding layer, said electrically conductive polymer sheet extending into said aperture of said electrically passive polymer cladding layer and physically and electrically contacting with said first metal layer;

forming an optical signal transmitting nonlinear optical polymer core layer onto said first electrically conductive polymer sheet;

forming a second electrically conductive polymer sheet onto said optical signal transmitting nonlinear optical polymer core layer;

forming a second electrically passive polymer cladding layer onto said second electrically conductive polymer charge sheet;

etching an aperture into said second electrically passive polymer cladding layer; and

depositing a second metal layer onto said second electrically passive polymer cladding layer and said metal layer extending metal also into said aperture physically and electrically contacting said second electrically conductive polymer sheet.

12. The method for fabricating a nonlinear optical polymer transverse electro-optic device of claim 11, including the step of providing nonlinear, electro-optic properties in said high data rate optical signal-transmitting nonlinear optical polymer core layer by applying heat and direct current voltage thereto.

13. The method for fabricating a high data rate nonlinear optical polymer transverse electro-optic device of claim 12, wherein said direct current voltage is 150 volts.

14. The method for fabricating a high data rate nonlinear optical polymer transverse electro-optic device of claim 12, wherein each said forming steps include the step of spin coating.

15. The method for fabricating a high data rate nonlinear optical polymer transverse electro-optic device of claim 14, wherein said steps for fabricating said first and second conductive polymer sheet layers include spin coating hydrochloric acid doped polyaniline.

16. The method for fabricating a nonlinear optical polymer transverse electro-optic claim 11, wherein said first and second electrically conductive polymer sheet layers each achieve a conductive polymer layer thickness of less than 0.1 micron.

17. The method for fabricating a high data rate nonlinear optical polymer transverse electro-optic device of claim 11, wherein said step of spin casting a high data rate optical signal transmitting nonlinear optical polymer core layer achieves a 1 micron or less nonlinear optic polymer core layer.

18. An electrically controlled, nonlinear optical polymer material-based transverse electro-optic method for switching and modulating a high data rate optical signal comprising the steps of:

transmitting a high data rate optical signal through a plurality of waveguides integral with a nonlinear optical polymer core layer;

applying an electric field to said nonlinear optical polymer core layer, said electric field commencing at a first conductive polymer sheet layer adjacent a first lateral surface of said nonlinear optical polymer core layer and terminating at a second conductive polymer sheet layer adjacent a second lateral surface of said nonlinear

optical polymer core layer. said electric field predictably altering an optical path curvature in said nonlinear optical polymer core layer; and

confining said high data rate optical signal within said nonlinear optical polymer core layer with electrically passive polymer cladding layers. a combination of said electrically passive polymer cladding layers and first and second conductive polymer sheet layers contributing to low optical signal propagation loss of said high data rate optical signal;

said altering of said optical path curvature in said nonlinear optical polymer core layer achieving a corresponding altering of waveguides performing said optical signal steps.

19. The electrically controlled. nonlinear optical polymer material-based transverse electro-optic method for switching a high data rate optical signal of claim **18**. wherein said step of applying an electric field to said nonlinear optical polymer core layer comprises supplying a first electrical potential to a first metallic layer communicating with said first conductive polymer sheet layer and a second electrical potential to a second metallic layer communicating with said second conductive polymer sheet layer.

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